

# **THE USE OF SEATING SYSTEMS TO REDUCE WHOLE BODY VIBRATION EXPOSURE IN THE SA INDUSTRY**



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I, Jessica Gunaselvam, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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## Abstract

The purpose of this study was to investigate the specification and use of appropriate seating systems to reduce whole-body vibration exposure in typical vehicles used in South African industry. As part of this study six suspension seats, which the manufacturers claim satisfy the requirements in ISO 7096 (2000), were tested. Six test subjects, three light and three heavy as specified in ISO 7096, were used to estimate the seat transmissibility functions in the vertical direction of the six different suspension seats. Transmissibility functions were measured in the laboratory using two excitation levels,  $1\text{m/s}^2$  and  $2\text{ m/s}^2$  *r.m.s.*, of broadband frequency vibration and a spectrum approximating the EM5 spectral class in ISO 7096. *SEAT* values were calculated for operational vibration data measured in an articulated dump truck and a three-wheeled logger. It was shown that *SEAT* values for the EM1 spectral class could not be reliably estimated from seat transmissibility functions and need to be measured directly in the time-domain. The measurement procedures and seat selection criteria developed in this research project were used to compile a set of "Design Guidelines for Seat Selection for Whole-Body Vibration Control in Industrial Vehicles". These guidelines will provide manufacturers with an easy-to-implement methodology to control whole-body vibration transmitted to the operators of industrial vehicles and to comply with international regulations for whole-body vibration transmission.

## Abstrak

Die doel van die studie was om die spesifikasies en gebruike van geskikte sitplek stelsels van uit Suid Afrikaanse industriële voertuie, wat heel-liggaam vibrasies verminder, te ondersoek. Ses suspensiesitplekke, wat deur die vervaardigers voorgeskryf word, is getoets om te sien of hulle aan die ISO 7096 (2000) vereistes voldoen. Ses persone, waarvan drie lig en drie swaar is, soos in ISO 7096 voorgeskryf, is gebruik om die sitplek oordragfunksies in die vertikale rigting vir die ses verskillende suspensiesitplekke te skat. Die oordragfunksies is in die laboratorium gemeet deur twee opwekkingsvlakke,  $1\text{m/s}^2$  en  $2\text{m/s}^2$  w.g.k., van wyeband frekwensie vibrasie en n spektrum beraam tot die EM5 spektrum soos in ISO 7096. 'SEAT' waardes was vanaf operationele vibrasie data wat in ge-artikuleerde vragmotors en driewiel-'loggers' gemeet is bereken. Daar is gewys dat betroubare 'SEAT' waardes vir die EM1 spektrum nie van sitplek oordragfunksies geskat kan word nie, maar dat dit eerder direk van die tyd-gebied afgelees moet word. Die metings prosedures en die sitplek keuse vereistes wat in die navorsingsprojek ontwikkel is, is gebruik om "Ontwerp Riglyne vir Sitplek Keuse Vereistes vir Heel-Liggaam Vibrasie in Industriële Voertuie" saam te stel. Hierdie riglyne sal vervaardigers met maklik toepasbare metodes toerus om heel-liggaam vibrasie, wat oorgedra word na industriële voertuig operateurs, te beheer en om aan internasionale regulasies t.o.v. heel-liggaam vibrasie oordrag te kan voldoen.



*To the glory of my LORD and Saviour, Jesus Christ!*

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## Nomenclature

$a$	Vibration acceleration, in $\text{m/s}^2$
$a_{A,z}$	Vertical acceleration at point A, one of three transducer mounting points in the cabin of the articulated dump truck, in $\text{m/s}^2$
$a_{B,z}$	Vertical acceleration at point B, one of three transducer mounting points in the cabin of the articulated dump truck, in $\text{m/s}^2$
$a_{\text{floor},z}$	Vertical acceleration on the cabin floor beneath the seat of the articulated dump truck, in $\text{m/s}^2$
$a_w$	Frequency-weighted acceleration, in $\text{m/s}^2$
$a_{w,\text{rms}}$	Frequency-weighted root mean square acceleration, in $\text{m/s}^2$
$f$	Frequency, in Hertz
$G_{ff}$	Power spectral density of the floor vibration
$G_{ij}$	Power spectral density function of the input
$G_{io}$	Cross-spectral density function of the input and output accelerations
$G_{oo}$	Power spectral density function of the output
$G_{ss}$	Power spectral density of the seat vibration
$H$	Transmissibility function
$H_{fs}$	Seat transmissibility function
$L$	Distance between points A and B, two of three transducer mounting points in the cabin of the articulated dump truck, in m
$r.m.s.$	Root mean square value, in $\text{m/s}^2$
$SEAT$	seat effective amplitude transmissibility
$T$	Duration of the measurement period, in s
$t$	Time, in s
$VDV$	Vibration dose value, in $\text{m/s}^{1.75}$
$W_i$	Relevant frequency weighting function for the human response to the vibration in the position and direction that is of interest
$W_k$	A frequency weighting applied to whole-body vibration to evaluate z-axis



	seat vibration with respect to comfort and health (ISO 2631-1, 1997)
x	Direction of fore-aft acceleration
y	Direction of lateral acceleration
z	Direction of vertical acceleration
$\gamma_{io}^2$	Coherence function
$\ddot{\phi}$	angular acceleration of point B relative to point A, two of three transducer mounting points in the cabin of the articulated dump truck, in rad/s <sup>2</sup>

## **Glossary**

ADT	Articulated dump truck
DSTF	Dynamic Seat Testing Facility
PSD	Power spectral density
WBV	Whole-body vibration

# 1. Introduction

## 1.1. Background

Whole-body vibration has been associated with industrial vehicles since their inception. The effects of vibration in the body depend on the extent to which vibration is transmitted to the body. The levels of vibration induced in the operators of industrial vehicles have the potential to infringe upon occupational health and occupational safety.

Though, the most common occupational health hazard to occur as a result of whole-body vibration exposure in industrial vehicles is low-back pain, other more debilitating musco-skeletal, spinal and gastro-intestinal problems can also result if the vehicle vibrations are severe. Long-term sick leave and early disability pensioning have been related to whole-body vibration induced diseases, which in turn have negative consequences for productivity. Occupational diseases caused by whole-body vibration exposure can also reduce the quality of the lifestyle of these drivers (Boshuizen *et al.*, 1990a, b).

Occupational safety in industry is impeded by the fatigue, visual impairment and loss of concentration experienced by drivers of industrial vehicles exposed to vibration. Driver fatigue is acknowledged as a serious problem, particularly in the case of long distance drivers of industrial vehicles, where it can result in collisions and fatal injuries to the driver and other parties (Mabbot, *et al.*, 2001).

In the past, the South African industry has paid little attention to the measurement and control of whole-body vibration. There is minimal quantifiable data, in particular epidemiological data, available for the assessment of exposure to harmful levels of whole-body vibration in the South African industry. However, an investigation by Van Niekerk *et al.* (1998),



conducted on mining vehicles in the South African mining environment, measured high levels of vibration in vehicles such as articulated dump trucks, front end loaders, tractor tippers, hydraulic face shovels, and bull dozers. These high levels of vibration were coupled to a high risk regarding health and safety for the drivers/operators. The study provides adequate evidence that the current whole-body vibration levels experienced by drivers of vehicles in the South African industry are not within acceptable international norms and thus pose health and safety threats due to increased risks.

In an effort to control whole-body vibration in industry, the European Union has issued the EU Directive 2002/44/EU to be legislated by 2005 in all European Union countries. The directive sets a whole-body vibration exposure limit of  $1.15 \text{ m/s}^2$ , and an action level of  $0.5 \text{ m/s}^2$  for an equivalent eight-hour exposure period as measured according to ISO 2631-1 (1997). The establishment of this directive is a result of the heightened awareness in first world countries of the detrimental effects of exposure to whole-body vibration in industry, on productivity and health. It is unlikely that similar limitations will be introduced in South Africa in the imminent future. However, industrial vehicle manufacturers in South Africa could jeopardize their European export market should their vehicles not comply with the vibration exposure levels specified in this directive.

## **1.2. Motivation**

The transmission of whole-body vibration occurs through contact of a subject with a source of vibration. The primary contact point for the above-mentioned transmission of vibration to drivers of industrial vehicles is through the seat cushion, directly beneath the ischial tuberosities ("sit bones"), Griffin (1990). The level of vertical vibration that is induced here will be influenced by several factors, including the road, vehicle suspension, speed of travel, the size of the driver or operator, the type of vehicle, and the seat characteristics.



Proper selection and use of seating systems is known to play a significant role in the exposure to and reduction of whole-body vibration, (Paddan and Griffin, 2001). Several mining and earth-moving vehicles use suspension seats which consist of a low-stiffness suspension mechanism (usually an air-spring and a damper) mounted below a relatively firm seat cushion. They have the capability to provide substantial vibration reduction in some environments but this is not the general rule as the efficiency of a seat depends on the input vibration spectrum as well the seat's dynamics. The usefulness of a particular suspension seat is determined by the frequency spectrum and amplitude distribution of the specific vibration environment (Griffin, 1990: p 399-404).

Occupied seat dynamics can be characterized by seat transmissibility functions, a non-dimensional ratio of the vibration at the seat interface to the vibration on the floor of the vehicle expressed as a function of the vibration frequencies. Although human vibration is not an exact science, reliable transmissibility measurements will be able to provide data on the seat's dynamic response and the response of the human body.

A set of design guidelines for the proper selection of suspension seats is necessary for the control of whole-body vibration in vehicles and can help promote a healthier and more comfortable working environment. It involves the development of test methods, analyses and selection criteria for seats subject to the type of vehicle and the type of vehicle operations.

### **1.3. Objectives and Aims**

The objectives of this study were to:

- **Develop a set of design guidelines for seat selection in the South African industry**

This is the primary objective of the project and aims to reduce the whole-body vibration exposure levels to drivers of industrial vehicles. These guidelines should provide the South African manufacturer of industrial vehicles with seat selection criteria that will help control the whole-body vibration levels to the drivers within the limits specified in the EU Directive 2002/44/EU. The design guidelines should contain guidance on testing procedures and analysis methods in order to ensure that seats are evaluated correctly for their vibration isolating (or attenuating) capabilities.

- **Create a database of road vibration affecting the seat selection in the South African industry**

This objective is concerned with initiating the collection of vibration data for operating conditions in vehicles in the South African industry. The vibration data that is measured in vehicles should provide sufficient information to calculate the vibration at the seat base of the vehicle. The pitch motion and roll motion can also provide important information, so their evaluation should preferably be permitted by the measured data.

- **Implement a test procedure to obtain reliable transmissibility measurements**

Transmissibility functions provide the ratios of seat vibration to the vibration at the seat base at all the frequencies under consideration. Transmissibility functions describe the frequencies of resonance for the vehicle vibrations (primary resonance and secondary resonance), the peak vibration amplification ratio of the seat and the attenuation of vibration by the seat at higher frequencies. Transmissibility data are influenced by several factors including the posture of the driver, the mass of the driver and the input signal. In order to



be able to compare the measurements of seats and develop seat selection criteria the test procedure that is implemented should provide reliable transmissibility results. The aims are to formulate a standard testing procedure to determine the seat transmissibility functions and to implement the procedure to evaluate seats.

- **Implement appropriate analysis methods for the evaluation of *SEAT* values from laboratory measurements and road vibration measurements**

*SEAT* values quantify the amount of vibration isolation a seat provides and are useful for selecting seats. Various international standards for seat evaluation, including ISO 7096 (2000), stipulate the estimation and measurement of *SEAT* values as part of the seat selection criteria.

- **Assess current seat selection in the South African industry**

This objective aims to use the seat transmissibility measurements and *SEAT* value calculations and the European Directive 2002/44/EU to assess the seats that are tested in this project for vehicles for which operational vibration is available for this project.

Due to the time and resources limitations imposed on this project, six suspension seats and two industrial vehicles were used as the basis of construction of seat selection criteria.

## **1.4. Layout of Thesis**

This document is intended to present the procedures, measurements, and results involved in the development of design guidelines for seat selection for whole-body control in industrial vehicles in the South African industry.

Chapter 2 deals with the literature survey on previous research. This chapter reports on the available international standards for the evaluation of seats in industrial vehicles, whole-body vibration measurements, seat transmissibility measurements, suspension seat dynamic characteristics, and the vibration environment of the South African industry.

Chapter 3 reports the vibration measurements carried out in an articulated dump truck and a three-wheeled logger. The vibration measurements for the articulated dump truck were conducted for operating conditions typical to the South African mining industry. Measurements on the three-wheeled logger were conducted for operating conditions typical to the South African forestry industry. The comparisons of the operational vibration data with the relevant ISO 7096(2000) input spectra are also compared in Chapter 3.

Chapter 4 describes the seat transmissibility measurement procedures, analyses and results for the measurements conducted on six suspension seats. The estimation of *SEAT* values for the six suspension seats are reported in Chapter 5.

Chapter 6 describes the development of seat selection criteria based on the measurements and estimations conducted in the preceding chapters. Chapter 6 also contains a copy of the "Design Guidelines for Seat Selection for Whole-body Vibration Control" that was developed in this project.

Chapter 7 contains the conclusions of this project and recommendations for future work.



## **2. Literature Survey**

### **2.1. International Standards**

Human vibration standards are aimed at providing standardized methods of measurement, evaluation and analysis to obtain values for the purposes of assessing and comparing vibration levels. Some standards even provide guidance on vibration limits that are not to be exceeded. The assessment of human response to whole-body vibration is complex in nature due to the diversity in the bio-dynamics of humans and the various ways in which it can be transmitted to the human body. Thus, any defining limits tend to be subjective in nature and should preferably be set by the organization responsible for their enforcement (e.g. governments, industrial organizations, companies, managers, unions).

There are several sub-categories of standards for whole-body vibration measurements and analyses due to the diversity of the applications. These sub-categories vary from measurement and analysis procedures, safety, instrumentation, to definitions of whole-body vibration vocabulary, etc. The standards that were employed in this project are tabulated in Table 2.1.

#### **ISO 7096 (2000)**

ISO 7096 (2000) stipulates a laboratory method for measuring and evaluating the effectiveness of the seat suspension in reducing the vertical vibration transmitted to the operator of earth-moving machines at frequencies between 1 Hz and 20 Hz. It is written in accordance with ISO 10326 -1 (1992) and also specifies seat acceptance criteria for different vehicles.

**ISO 10326-1 (1992)**

This International Standard specifies the test method, the instrumentation requirements, the measuring assessment method and the way to report the test result for the laboratory testing of vibration transmission through a vehicle seat to the occupant. This standard applies to specific laboratory seat tests which evaluate vibration transmission to the occupants of any type of seat used in vehicles and mobile off-road machinery.

**ISO 2631-1 (1997)**

This International Standard defines methods for the measurement and evaluation of whole-body vibration and indicates the principal factors that combine to determine the degree to which the vibration exposure will be acceptable. It considers vibration in the frequency range of 0.5 Hz to 80 Hz for the evaluation of the effects on health.

**Table 2.1 International Standards applied to this project**

ISO 7096 (2000)	Earth-moving machinery: Laboratory evaluation of operator seat vibration
ISO 10326-1 (1992)	Mechanical vibration – Laboratory method for evaluating vehicle seat vibration – Part 1: Basic requirements
ISO 2631-1(1997)	Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements
ISO 13090-1 (1990)	Mechanical vibration and shock – Guidance on safety aspects of tests and experiments with people – Part 1: Exposure to whole-body mechanical vibration and repeated shock



### **ISO 13090-1 (1990)**

This International Standard provides guidance on the safety aspects of the design of equipment and method of tests and experiments in the laboratory in which human subjects are exposed to mechanical vibration and repeated shock.

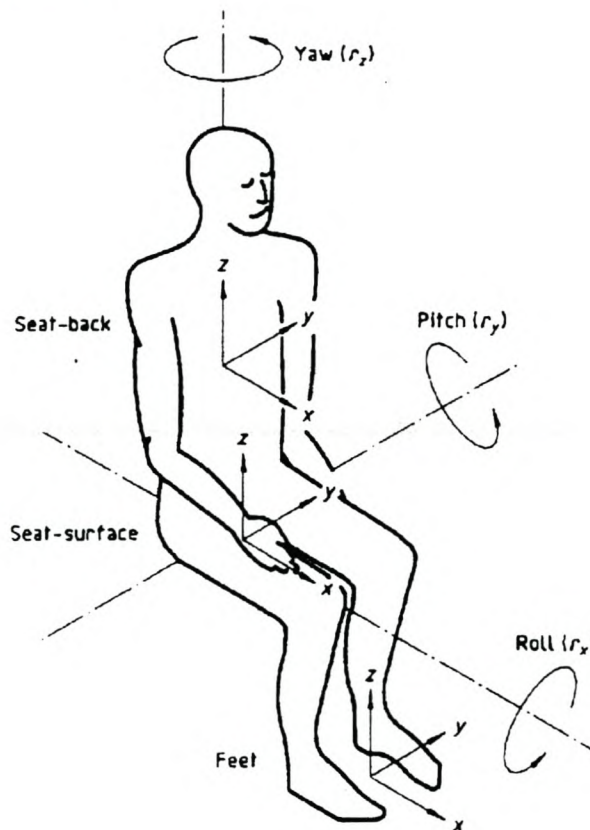
## **2.2. Whole-Body Vibration Measurements**

Whole-body vibration takes place when the human body comes into contact with, or is supported by, a vibrating surface. This usually occurs if the person is sitting on a vibrating seat, standing on a vibrating floor, or lying on a vibrating bed. Measurements of whole-body vibration are carried out to quantify and report vibrations to which humans are exposed to. These quantities are related to the measurement procedures that were used. Standard procedures for measurement and evaluation of whole-body vibration have to be established in order to obtain 'satisfactory' information of vibration severity, and allow for comparison of data. The International Standards Organization has documented several standard procedures for the measurement and evaluation of whole-body vibration. Some of these international standards have been described in the preceding section.

Instrumentation for the measurement and recording of whole-body vibration include transducers and signal conditioning equipment, analogue-to-digital converters and a data analyzer. A transducer is a device for converting mechanical motion into electrical charge. Accelerometers are the most common transducers used in whole-body vibration measurements, they produce an electrical output proportional to acceleration. Transducers are connected to some form of signal conditioning, to provide power to the transducer in addition to amplifying and filtering the vibration signal before it is passed to the data analyzer. The analogue to digital converter converts the

conditioned, filtered, analogue voltage signal to a digitized computer record. The data analyzer enables visual inspection of the acquired signals during measurement and provides a means of storing the signals in a useful digitized form in a computer.

The three orthogonal axes of measurement for whole-body vibration are defined in ISO 2631-1 (1997). The International Standard defines the z-axis in the vertical direction passing from the seat to the head of the operator (for seated persons) or from the feet to the head of the operator (for standing persons). The x-axis is defined in the direction of travel and the y-axis is in the direction transverse to it (see Figure 2.1).



**Figure 2.1** Co-ordinate system for mechanical vibration influencing humans as defined in ISO 2631-1 (1997)



Human response to vibration is dependent on the frequency content of the signals. ISO 2631-1 (1997) defines various frequency weighting curves which reflect the known and hypothesized relationships between vibration frequency and the various human responses.

The analysis of whole-body vibration usually involves either the amplitude composition or the frequency composition of the vibration time data. Some of the amplitude analysis methods are the root-mean-square (*r.m.s.*), the vibration dose value (VDV), and the crest factor. The power spectral density function is an example of frequency analysis.

For acceleration measurements, the frequency-weighted root-mean-square (*r.m.s.*) acceleration,  $a_{w,rms}$  expressed in meters per second squared ( $m/s^2$ ) can be calculated using:

$$a_{w,rms} = \left[ \frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}} \dots\dots\dots (2.1)$$

where  $a_w(t)$  is the weighted acceleration as a function of time in meters per second squared ( $m/s^2$ ), and  $T$  is the duration of the measurement period in seconds (s).

The crest factor is defined as the ratio of the peak weighted acceleration value to the complete signal's corresponding weighted *r.m.s.* value.

Vibration dose value (VDV) is the cumulative measure of the vibration and shock received by a person for the period of measurement. The VDV is expressed in  $m/s^{1.75}$  and is given by the integral of the fourth power of the frequency-weighted acceleration,  $a_w(t)$ :

$$\text{VDV} = \left[ \int_0^T a_w^4(t) dt \right]^{\frac{1}{4}} \dots\dots\dots (2.2)$$

The VDV has the advantage that it is not limited to low crest factor motions and it may be applied to intermittent vibration exposures, to repeated shocks and also to those exposures consisting of periods of vibration at different magnitudes. It also incorporates an indication of the dose as it is not time normalized.

The power spectral density (PSD) function of an acceleration time series is the distribution of the mean square value of the accelerations over frequency, and is expressed in  $(\text{m/s}^2)^2/\text{Hz}$ .

Pradko, et al (1965) found that the transfer function is useful in the analysis of whole-body vibration measurements.

### 2.3. Seat Transmissibility Measurements

Seat transmissibility is the non-dimensional ratio of the amplitude of the vibration at the seat-human interface to the amplitude of the vibration of the excitation beneath the seat expressed as a function of the vibration frequencies. It is used to characterize the ability of a seat to isolate (and also amplify) road vibrations.

The most direct method of seat transmissibility measurement is achieved by comparing the acceleration on the seat with that of the base. These measurements can be conducted in the laboratory or in the vehicle. The laboratory measurements have several advantages. This includes the testing of several seats for the same vehicle with the condition that an acceptable input



spectrum is simulated to represent the real-life vibration for which isolation is required.

Transmissibility data in a vehicle is obtained from signals supplied by accelerometers mounted at the base of a seat (e.g. floor attachment points) and at the interface between the seat surface and the human body. It is important that the transducers do not compress the seat to alter the dynamic properties at the seat-person interface. Mounting the accelerometers in a SAE seat pad or SIT-BAR (Griffin, 1990) is often suitable for the prevention of seat compression by the transducers.

Transmissibility can be measured in any axis and vibration in one axis can cause vibration in another axis, for example the vertical floor vibrations in a vehicle can cause fore-aft vibration in the backrest. The studies conducted to date have been mostly concerned with vertical transmissibility from the seat base to the ischial tuberosities (sit bones). Nelson and Lewis (1989) measured seat vibration in six vehicles on different roads and found that the vertical vibration on the seat was greater than the fore-aft and lateral vibrations in every case.

It is necessary to recognize that seats are multiple-input multiple-output systems. A coherence function is used to supply a good estimation of the output vibration that is exclusively due to the measured input vibration. The computation of partial coherence functions may be required to obtain a better understanding of the seat vibration transmission in a given axis. In the case of vertical vibration transmission useful information can be obtained with the assumption that the seat is a single-input single-output system, and thus only computing ordinary coherence functions.



Road vibration measurements to obtain seat transmissibility functions in vehicles have several disadvantages. They might not be statistically stationary or representative of other input signals and may not contain sufficient energy at all frequencies. Thus the seat transmissibility function calculated from field measurements may not be well defined at some frequencies and therefore cannot always be assumed to apply to a different vibration input.

Laboratory seat transmissibility measurements are undertaken when seat transmissibility measurements cannot be undertaken in the vehicle. These measurements have the added advantage that since the input spectrum can be controlled it is possible to determine the transmissibility at all frequencies. It is also possible to measure transmissibility in each axis without the concern of multiple coherency measurements.

Seats can have significant non-linear dynamic behaviour. In suspension seats these non-linearities can be caused by friction and gaps between moving parts in the suspension. Fairely (1983) reported non-linear behaviour in a foam-and-spring seat. The study found that the resonance frequency of the seat decreased with increasing vibration magnitude. This effect was also observed by Corbridge (1987) in an investigation on the transmission of vertical vibration to the seat-person interface of a rail vehicle passenger seat. Griffin and Wu (1996) confirmed similar effects for suspension seats.

The non-linear behaviour in seats can cause the transmissibility measured in the laboratory to be different to the transmissibility measured in the vehicle if the spectrum of vibration used in the lab differs greatly from that in the field. Employing the vehicle spectra in the laboratory however may prevent the determination of the transmissibility function at all frequencies. Therefore it is recommended (Griffin, 1990) that in addition to using a recorded vibration it can also be beneficial to determine the transmissibility of a seat with standardized

broadband random vibration presented at say two vibration magnitudes representing the lowest and highest encountered in the vehicle.

Corbridge (1987) also investigated the effects of subject weight, sex and posture on seat transmissibility. It was concluded that seat transmissibility was insensitive to subject weight and sex and the correlation of these characteristics on the magnitude and frequency of peak transmissibility were generally low. There was some, although insignificant, negative correlation that was observed between both the subject weight and the peak transmissibility. The upper body posture was reported to have significant effects on the seats. Changing leg position, however, had relatively little effect on the measured transmissibility.

Stayner (1972) studied tractor suspension seats and found that heavier drivers were usually better isolated from vibration by these seats than the lighter test subjects. The build of the subjects can have an effect of the same order as the weight of the subjects.

## **2.4. Suspension Seats**

Suspension seats consist of a low-stiffness suspension mechanism supported below a relatively firm seat cushion. Conventional occupied seats usually have a natural frequency close to 4 Hz and many vehicles have significant energy at this frequency. In order to achieve isolation the natural frequency of the seat needs to be lowered to well below the frequency of the vibration. The only approach to lowering the natural frequency will be to reduce the stiffness. A considerable reduction in stiffness is required to lower the natural frequency, to halve the natural frequency the stiffness has to be divided by four. The resulting softness of the conventional seat tends to have poor static comfort and little stability against roll motion. Suspension seats could provide a solution to this problem as they have lower natural frequencies.



The suspension mechanism of a suspension seat is usually a passive mechanism consisting of a damper and some form of spring. The spring may be a steel spring or an air spring. The seats can have large deflections due to the low stiffness of their mechanisms. They have to be adjusted to the test subject's weight to ensure that the seat is operated about its mid-position. The seat needs to be adjusted manually for seats with steel springs, while air suspension seats usually detect the seat deflection and adjust automatically to the occupant's weight.

Several commercial and industrial vehicles employ suspension seats. These include trucks, coaches, tractors and other off-road vehicles. Suspension seats can be used for vibration control in most environments. The usefulness of suspension seats for whole-body vibration control is determined by the vibration spectrum of the vehicle in a given environment as well as the seat's dynamic characteristics.

A comparison between a conventional seat and a suspension seat in Griffin (1990) indicated that the suspension seat attenuates vibration above about 3 Hz while the conventional seat only attenuated vibration above about 5 Hz. The suspension seat was found to be superior to the foam seat between about 2-12 Hz; the converse was true for frequencies below 2 Hz and for higher frequencies.

Suspension seats are expected to amplify vibration at 1-2 Hz. This is dependent on the seat characteristics due to the non-linearities present in these seats (Wu and Griffin, 1996). The efficiency of these seats will depend on whether the amplification at resonance is adequately offset by the attenuation at higher frequencies.



Boileau and Rakheja (1990) evaluated four different types of suspension seats in the laboratory and in the field in order to measure their adaptability for attenuating whole-body vibration in log skidders used in the forest industry. Each seat was tested in the laboratory using sinusoidal excitations. The seats were also tested in the field during normal skidding operations. There was generally good agreement between the transmissibility characteristics measured in the laboratory and in the field. The transmissibility data of the seats were evaluated against the transmissibility data measured on a rigid seat. The results revealed that three of the seats possess the desired transmissibility characteristics for attenuating the vibration encountered on skidders.

## **2.5. Vibration Environment of the South African Industry**

Whole-body vibration has been associated with industrial vehicles and is generally experienced through high-amplitude, instantaneous shock excitation and through repeated regular low-amplitude motion over rough terrain. The type of terrain and the type of industrial vehicle influences the levels of whole-body vibration experienced by the operators. The maintenance condition and age of a vehicle is also known to influence vibration transmission. Vehicles that are outdated, poorly maintained, and have operational lives long past the norm can increase the transmission of whole-body vibration and increase the risk of harmful effects to the operators (Joubert, 2002).

South Africa has paid little attention to whole-body vibration exposure in industry due to the fact it is difficult to evaluate, quantify and control. The industries in South Africa that could have possible whole-body vibration health concerns can be broadly categorized as the mining industry, forestry industry, agricultural industry, and civil construction/earth-moving.

The vehicles in the South African mining industry can be classified as transport equipment and include articulated dump trucks, locomotives, shuttle cars and utility vehicles. A study by Van Niekerk *et al* (1999) was one of the earliest studies that attempted to quantify whole-body vibration in these vehicles in the South African mining environment. The vibration assessment involved tri-axial measurements at the seat surface. Measurement and evaluation of the vibration data were based on the ISO 2631-1 standard. Most of the measurements were conducted in the actual workplace or in the field. The results indicate that for a front-end loader, an articulated dump truck, tractor tipper, a hydraulic face shovel, and a bulldozer the weighted *r.m.s.* values are all above  $1.0 \text{ m/s}^2$ . According to ISO 2631-1 a level of  $1.0 \text{ m/s}^2$  lie within the health guidance caution zone for 4-8 h operations. It is necessary to point out that these measurements were conducted under extreme conditions and only reflect the vibration at a selected time in the day. The data could therefore not be a true reflection of the actual level of vibration averaged over the whole 4-8 hour period. The results can however serve as an indication that there might be a need for whole-body vibration reduction in these vehicles to improve the health and safety of their operators.

An ergonomic survey of the South African forestry industry by Warkotsch (1994) included an investigation of whole-body vibration exposure levels in three and four- wheeled loggers. In-field seat vibration measurements were obtained for operations such as roadside stacking, extraction in a pine plantation and a eucalyptus plantation the VDV values were in the range  $19.2 - 22.9 \text{ m/s}^{1.75}$ . Based on BS 6841 (1987), a VDV of  $15 \text{ m/s}^{1.75}$  would provide for an exposure period of 4 h per working day before the vibration levels would become a health hazard to the operator of the vehicle. From the results it is clear that the operators of three and four-wheeled loggers are being subjected to high levels of vibration that can pose a health risk.



Joubert (2002) reported a pilot study investigating the whole-body vibration exposure levels in forklifts in the South African industry. Vertical seat vibration measurements were conducted on nine forklifts that were operational at the port of Durban, South Africa. The study considered rough versus smooth terrain as well as seat adjustment. There were two settings considered in the seat adjustment, one at its lowest setting (i.e. with no damping) and one adjusted to the driver's specific weight according to manufacturer specifications. ISO 2631-1 (1997) was again implemented in the measurement and analysis. Assessment of vibration was according to EEC Machinery Directive, which recommends an action level of  $0.50 \text{ m/s}^2$  for an 8 h exposure period and stipulates an exposure limit level of  $0.70 \text{ m/s}^2$ . Results indicated that all the *r.m.s.* values of the measurements exceeded  $0.50 \text{ m/s}^2$  and 82% of the *r.m.s.* values exceeded  $0.70 \text{ m/s}^2$ . In fact some of the results indicated *r.m.s.* values as severe as  $3.05 \text{ m/s}^2$ . The results also showed that the vibration levels experienced over rough surfaces (mean *r.m.s.*  $1.40 \text{ m/s}^2$ ) were higher than on smooth surfaces (mean *r.m.s.*  $0.92 \text{ m/s}^2$ ). The seat adjustment had some effect on the vibration levels, with the unadjusted seat transmitting more vibration. However, with mean values for these operational conditions the statistical difference in whole-body vibration exposure levels between adjusted ( $1.00 \text{ m/s}^2$ ) and unadjusted seats ( $1.02 \text{ m/s}^2$ ) were not significant.

## 2.6. Conclusions

The diversity in the bio-dynamics of humans results in the assessment of human response to whole-body vibration being complex in nature. Human vibration standards provide standardized methods of measurement, evaluation and analyses to obtain values for assessing and comparing vibration levels.

Measurements of whole-body vibration are carried out to quantify and report vibrations to which humans are exposed and to assess the harmful effects of



such vibrations. The instrumentation for the measurement and recording of whole-body vibration include transducers and signal conditioning equipment, analogue-to-digital converters and a data analyzer. The frequency content of the signals determines the human response to vibration. The axes of vibration measurement and the frequency weighting curves for human response to whole-body vibration are defined in ISO 2631-1 (1997). The most common methods of analyzing whole-body vibration measurements are the weighted root-mean-square (*r.m.s.*) acceleration, the weighted vibration dose value (VDV), the crest factor, the power spectral density function and the transmissibility function.

Seat transmissibility is used to characterize the ability of a seat to isolate (and also amplify) road vibrations. The most common method of seat transmissibility measurement is achieved by comparing the vertical acceleration at the seat with that of the seat base. These measurements can be conducted in the laboratory or in the vehicle. The transmissibility in one axis may be a result of vibration in another axis. A coherence function provides a correlation between the input and the output and needs to be determined in transmissibility measurements. Transmissibility functions are influenced by factors such as the posture and weight of the test person and the type of input signal.

Suspension seats have a separate suspension system and can be used for vibration control in most environments. The usefulness of suspension seats for whole-body vibration control is determined by the vibration spectrum of the vehicle in a given environment as well as the seat's dynamic characteristics. Suspension seat generally amplify vibration at 1-2 Hz and attenuate vibration above about 3 Hz.

There is very little whole-body vibration data available for the industries in South Africa. However, the studies that have been conducted on vehicles and

machinery in the mining industry, forestry industry, agricultural industry, and civil construction/earth-moving industries of South Africa suggest that the whole-body vibration levels that the operators are exposed to have the potential to infringe on occupational health and safety.



## 3. Vibration Environment

### 3.1. Introduction

The vibration environment in which the vehicle is operated significantly influences the performance of a seat in attenuating vibration transmitted to the operators of vehicles. The level and the frequency content of the vibration at the seat base characterize the vibration environment. In an effort to study the vibration environment of the South African industry two typical industrial vehicles were considered as case studies. The vibration levels in an articulated dump truck and a three-wheeled logger were measured (Appendix A.1 shows photographs of similar vehicles). The testing procedure and data analysis for these measurements are presented in Sections 3.2 and 3.3. The South African mining and forestry industries were represented by the operations in the articulated dump truck and the three-wheeled logger respectively. Section 3.4 compares the power spectral densities of the vibration in the vehicles with the prescribed input spectral classes in ISO 7096 (2000) for evaluating seats in earth-moving machinery.

Power spectral density functions describe the frequency distribution of the power in a time history per unit of frequency. Root mean square values (*r.m.s.*) on the other hand provide an indication of the level of intensity of the vibration exposure. The *r.m.s.* values can be determined from the power spectral densities of the vibration signals, as in Chapter 5. The *r.m.s.* value corresponding to any frequency band is calculated by multiplying the power in the band by the width of the band and obtaining the square root.

The vibration environment in this project refers to the human exposure to vibration. The vibration data needs to be frequency-weighted in order to reflect the human response.  $W_k(f)$  is the relevant frequency weighting in the vertical direction at the seat top according to ISO 2631-1 (1997).



### 3.2. Articulated Dump Truck Operations

Articulated dump trucks are in general used for moving large volumes of dirt, sand or gravel in the mining, forestry and construction industries. An articulated dump truck with a 40 ton payload capacity was used in this study to determine typical vibration exposure levels in the South African mining industry. Measurements were carried out to determine the vertical vibration levels at the base of the seat, to conform to the scope of the project. The articulated dump truck was driven unloaded over typical road conditions. The following types of operating conditions were represented:

- Vehicle stationary with engine idling
- Travelling at moderate speed on a tar road
- Travelling at moderate speed on a reasonable gravel road
- Travelling at low speed on a bad gravel road
- Travelling at moderate speed on a corrugated road

Three channels of vertical acceleration measurements on the cabin floor were used to ascertain the vertical stimulus beneath the operator's seat surface. These positions include two rear cabin measurements (i.e. at the right and the left) and one front cabin measurement as illustrated schematically in Figure 3.1 (refer Appendix A.2 for 3-D drawings of the cabin measurements set-up). The time duration of each measurement was 60 seconds. The signals were low-pass filtered to prevent aliasing and sampled at 500 Hz. Only data up to 25 Hz was used for the analysis.

The cabin was assumed to be rigid for the frequency range of interest in the analysis and the vibration on the floor beneath the seat was calculated using the following equation based on rigid body dynamics:

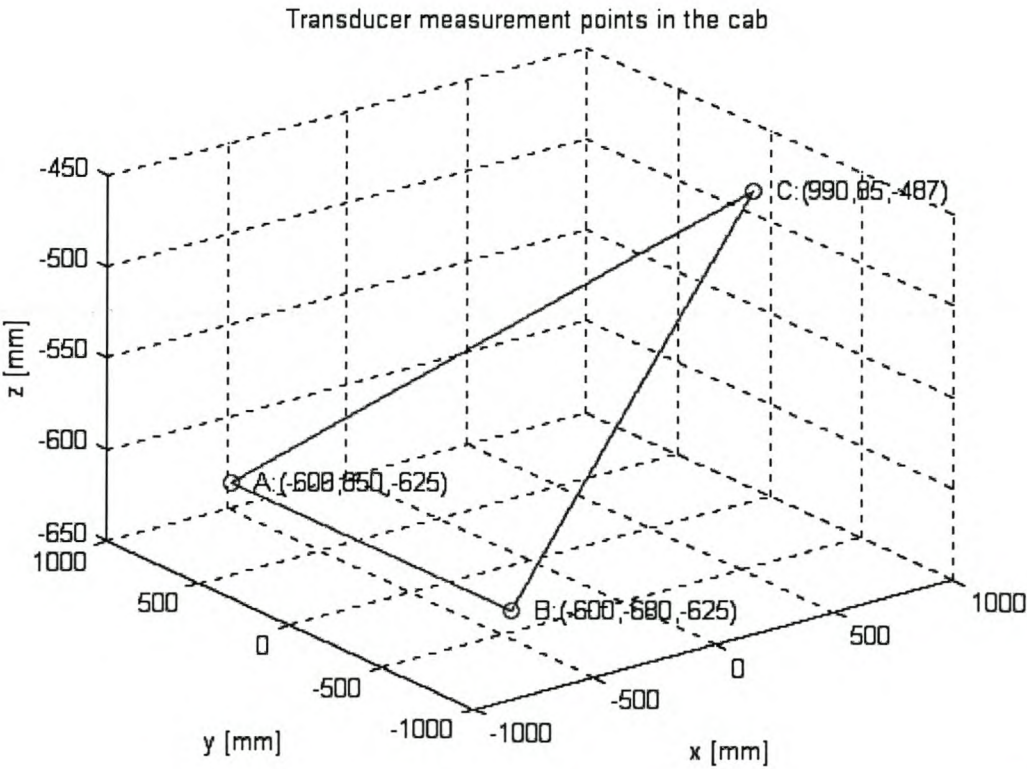
$$a_{\text{floor},z} = a_{A,z} + \frac{L}{2} \ddot{\phi} \dots\dots\dots (3.1)$$

Where  $a_{\text{floor},z}$  is the vertical acceleration on the cabin floor beneath the seat,  $a_{A,z}$  is the vertical acceleration at point A (refer Figure 3.1), and  $L$  is the distance between points A and B. This principle is an extension of linear interpolation and thus can only be applied if the body is rigid.

$\ddot{\phi}$  is the angular acceleration of point B relative to point A in Figure 3.1 (i.e. the roll of the vehicle) and is defined by:

$$\ddot{\phi} = \frac{(a_{B,z} - a_{A,z})}{L} \dots\dots\dots (3.2)$$

where  $a_{B,z}$  is the vertical acceleration at point B.



**Figure 3.1** Schematic of the transducer mounting positions for vertical cabin floor acceleration measurements in the articulated dump truck

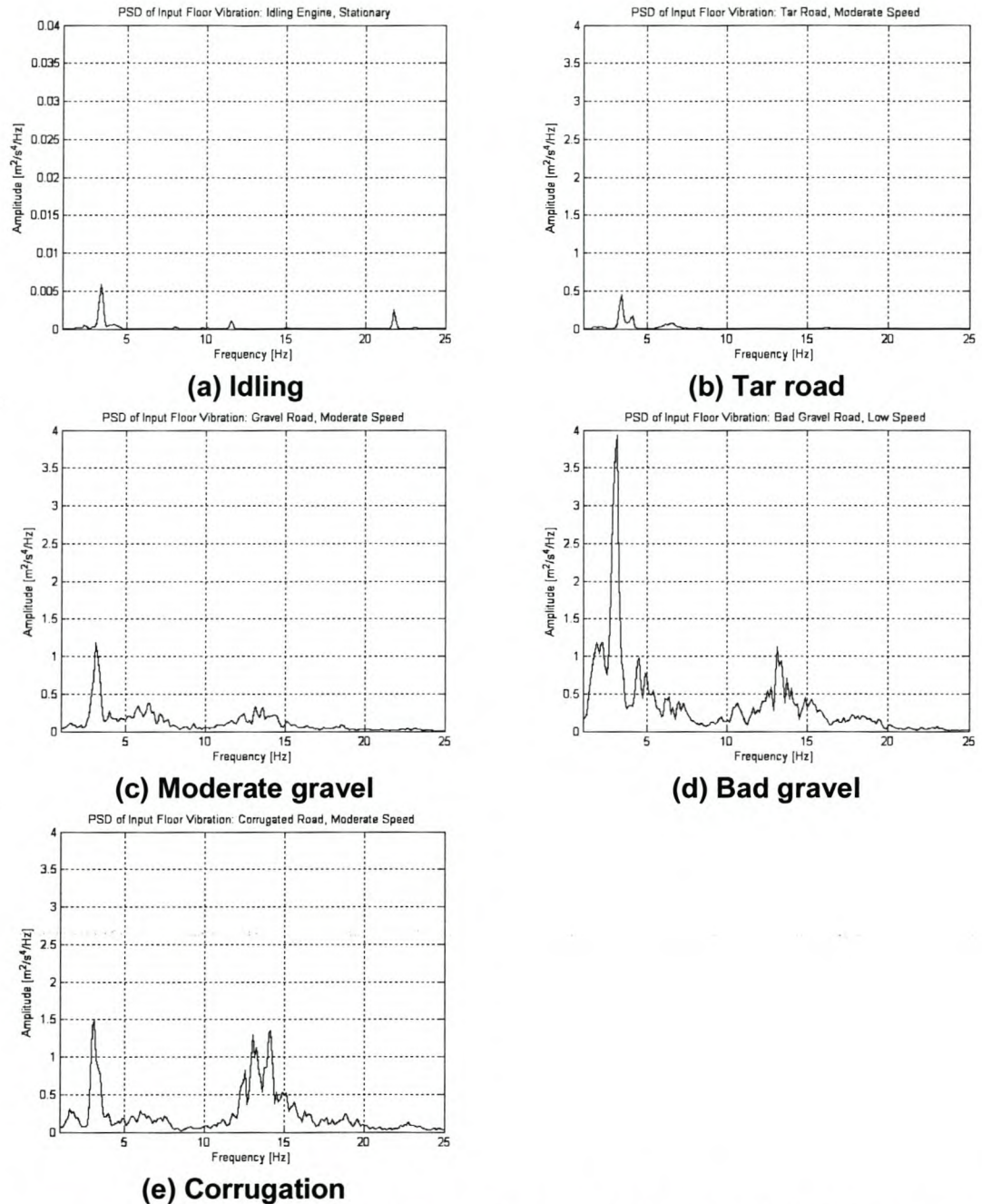


The angular acceleration around the y-axis (i.e. the pitch of the vehicle) was not considered in this study. The mid-point of line AB was chosen out of convenience and the accelerations at this point are taken as a reasonable estimate of the vertical accelerations on the floor directly beneath the seat, as in Equation (3.1).

The vibration estimates at the base of the seat were analysed for frequency content and level of vibration exposure. The power spectral densities of the vibration at the seat base for each of the operating conditions are shown in Figure 3.2. The frequency analysis used 1024 points, a frequency resolution of 0.488 Hz and 52 degrees of freedom (Griffin, 1990: p 474).

In Figure 3.2 it is important to note that the maximum limit on the vertical axis of the power spectral density function for the idling operation is  $0.04 \text{ (m/s}^2\text{)}^2/\text{Hz}$ , whereas this limit for all the other operations is  $4.0 \text{ (m/s}^2\text{)}^2/\text{Hz}$ . From this figure it can be seen that operations on tar road has the lowest vibration energy while the operations over 'bad gravel' road has the highest vibration energy. The power spectral densities also indicate that for the higher vibration intense operations, namely (c) to (e), the vibration energy is distributed over the frequency range 1-25 Hz. In these cases there are two resonances that are exhibited. There is a primary resonance between 2-4 Hz that represents the rigid body modes of the cab frame. Secondary resonance between 10-15 Hz may represent the wheel-hop mode of the cab-wheels axle.

Table 3.1 lists the un-weighted and weighted *r.m.s.* values of the vibration data for the operations measured in the articulated dump truck. The *r.m.s.* values were computed from the respective power spectral density functions.



**Figure 3.2** PSD plots of input floor vibration in the articulated dump truck (0.488 Hz frequency resolution, 52 degrees of freedom)

The EU Directive 2002/44/EU has set for whole-body vibration an exposure limit of  $1.15 \text{ m/s}^2$  and an action level are  $0.5 \text{ m/s}^2$ , for an equivalent 8-hour exposure period. The results show that the weighted *r.m.s.* values for the



operations in the ADT, with the exception of idling, exceed the action level that is recommended by the directive. Operations over moderate gravel, bad gravel and corrugated roads have values that are either at or exceed the exposure limit stipulated in the directive. The correct seat can assist to reduce these levels to below the levels proposed by the EU Directive.

**Table 3.1** Computed *r.m.s.* values of the operational vibration data measured in the ADT

Operation	Un-weighted <i>r.m.s.</i> accelerations [m/s <sup>2</sup> ]	Weighted <i>r.m.s.</i> accelerations [m/s <sup>2</sup> ]*
Idling	0.33	0.13
Tar road	0.69	0.56
Moderate gravel	1.72	1.50
Bad gravel	2.94	2.43
Corrugation	2.46	2.00

\*Calculated with the frequency weighting  $W_k(f)$ , ISO 2631-1.

### 3.3. Three-Wheeled Logger Operations

Three-wheeled loggers are commonly located at forestry sites. They are mainly used to transport logs to the roadside over short distances over rough forest terrain. Operators are also required to drive the unloaded vehicles over dirt road to and from their place of work. Vibration measurements were carried out in a three-wheeled logger for operations typical to the South African forestry industry. The operations represented were:

- Short run at slow speed on forest terrain with loading and unloading operations
- Long run at moderate speed on a corrugated dirt road, unloaded

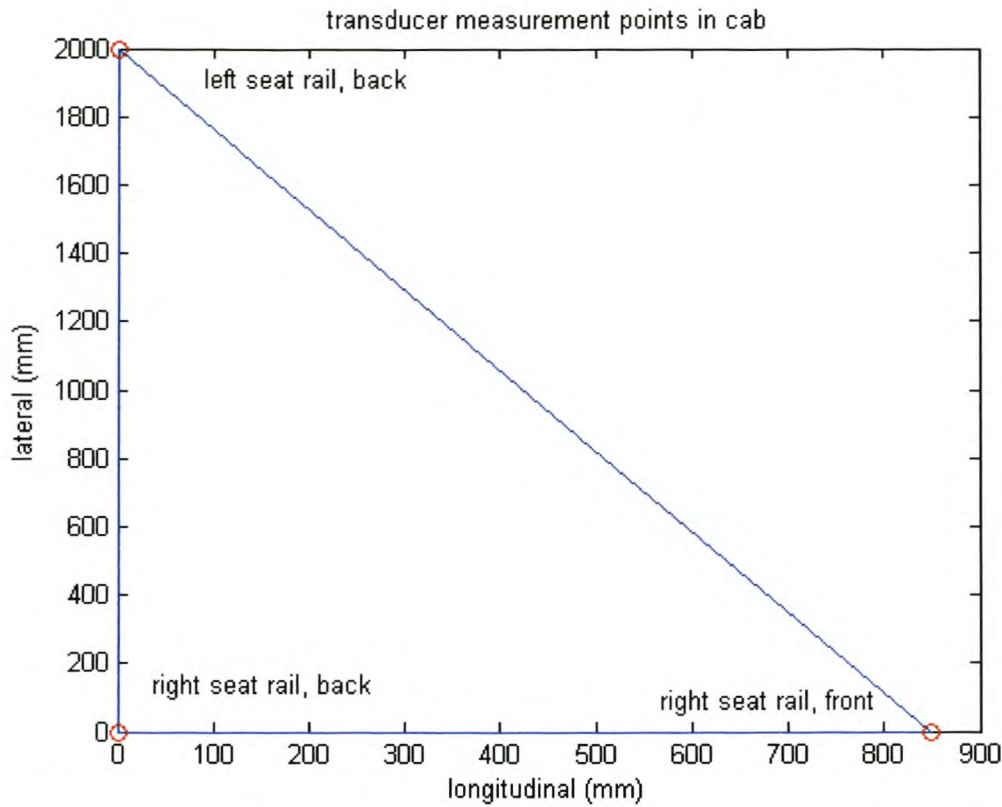
Vehicle speeds between 20 – 25 km/h were observed. The operator for the tests was a male subject, 1.85 m tall and weighing 82 kg. The temperature inside the cabin was 16 °C.

The vertical acceleration on the floor beneath the seat was averaged from three channels of vertical acceleration measurements. This was accomplished by two PCB Piezotronics single axis accelerometers that were magnetically mounted to the ends of the seat rails. Two accelerometers on the right seat rail and one on the rear end of the left seat rail (see Figure 3.3). The accelerometer mounted at the front end of the right seat rail formed one channel in a tri-axial vibration measurement. The vibration acceleration data in the fore-aft (x-axis) and lateral (y-axis) directions are available for future studies but are not considered here.

Vibration on the seat surface was measured using a PCB Piezotronics seat pad with tri-axial accelerometers (Model No. 356B40, SN 21385) in the directions defined in ISO 10326-1 (1992). The accelerometers were positioned at the centre of the seat and the operator was requested to sit firmly on it. The seat pad was taped to the seat surface. Only the seat vibration in the vertical direction (z-axis) was analysed in this project.

Data acquisition of the acceleration signals was achieved by two commercial computer-based data acquisition and analysis systems, SigLab (version 3.2.6). The time duration of each measurement was 250 seconds. The signals were low-pass filtered and sampled at 256 Hz. Only data up to 25 Hz was used in the analysis.

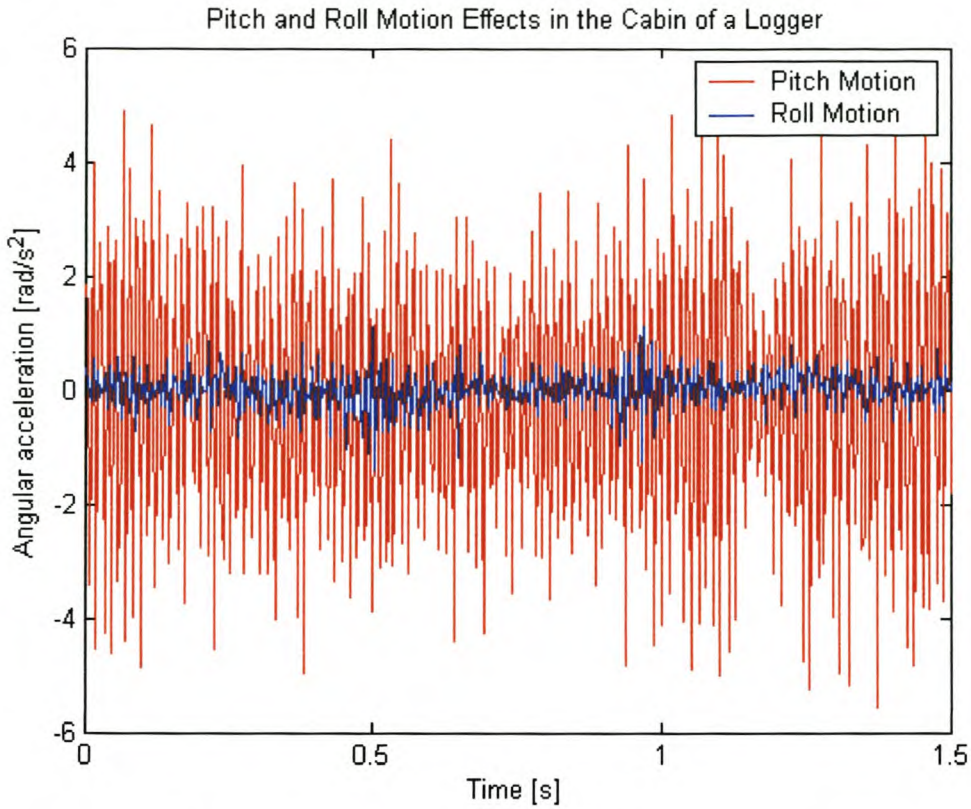




**Figure 3.3** Schematic of the transducer mounting positions for vertical cabin floor acceleration measurements in the three-wheeled logger

The pitch and roll motions in the cabin were analysed using rigid body dynamics as was described in Equations (3.1) and (3.2) in the preceding section. The effects of roll motion were ascertained from the acceleration measurements from the accelerometers on the rear ends of the seat rails (i.e. right rear and left rear). Pitch motion effects were ascertained from the accelerometer measurements on the front and rear ends of the right seat rail.

Figure 3.4 describes the relative effects of roll and pitch motions in the cabin. These effects are represented by the angular accelerations evident around the fore-aft (x-axis) and lateral (y-axis) directions respectively (Equation (3.2)). The acceleration measurements at the rear end of the right seat rail were used as the reference in these calculations.

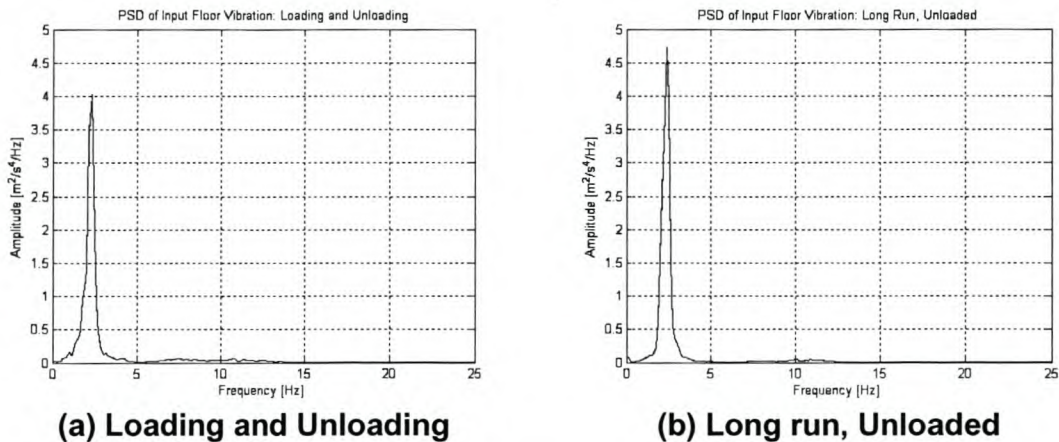


**Figure 3.4** Pitch and roll motions in the cabin of a three-wheeled logger for loading and unloading operations over forest terrain

The angular accelerations in Figure 3.4 were determined for the loading and unloading operation. Only a portion of the time history was selected for presentation purposes. It is clearly evident from the figure that the roll motion in the cabin is relatively negligible compared to the pitch motion. The results are also consistent with complaints of excessive motion in the fore-aft direction during operations made by the drivers of the vehicle. These relative comparisons between pitch and roll motion effects also extends to the measurements conducted on a long run over dirt road. Computations of the acceleration at the seat base in this study thus only accounted for the pitch motion.



Power spectral densities of the vibration estimates at the base of the seat were computed with 1024 points, a frequency resolution of 0.250 Hz and 52 degrees of freedom (Griffin, 1990: p 474). These spectra are presented in Figure 3.5.



**Figure 3.5** PSD plots of input floor vibration in the three-wheeled logger (0.25 Hz frequency resolution, 52 degrees of freedom)

The power spectral densities obtained for the operations in the three-wheeled logger have a low frequency content, limited to a few Hertz (1- 4 Hz). Only one resonance, due to the rigid body mode of the vehicle, is evident in the operations. There is no evidence of wheel-hop from the front axle in this vehicle, which generally occurs in the frequency range (10-15 Hz), and is explained by the absence of a primary suspension system in the vehicle.

Un-weighted and weighted *r.m.s.* values were computed for the operations from the respective power spectral density functions. The weighted *r.m.s.* values were also computed for the vibration data measured at the seat interface. Table 3.2 lists the weighted *r.m.s.* values for the operational vibration data in the three-wheeled logger.

The weighted *r.m.s.* values in Table 3.2 indicate that the action level in the EU Directive 2002/44/EU for whole-body vibration exposure is exceeded for the operations. This project tackles the transmission of vibration through the ischial

tuberosities (sit bones) of the operator. The last point of contact for vibration transmission is at the seat interface. The weighted *r.m.s.* values at the seat interface for the current seat in the three-wheeled logger is higher than if the operator were seated on the floor. This indicates a poor seating selection for these combinations of vehicle and operations. The table also shows that the *r.m.s.* values on the seat surface are above the exposure limit stipulated in the EU Directive. Further testing is necessary to suggest more optimal vibration control through seat selection.

**Table 3.2** Computed *r.m.s.* values of the operational vibration data measured in a three-wheeled logger

Operation	Weighted <i>r.m.s.</i> accelerations at the seat base [m/s <sup>2</sup> ]*	Weighted <i>r.m.s.</i> accelerations at the seat interface [m/s <sup>2</sup> ]*
Loading and Unloading	1.14	1.28
Long run, Unloaded	1.14	1.41

\*Calculated with the frequency weighting  $W_k(f)$ , ISO 2631-1.

### 3.4. Seat Evaluation Input Spectra from ISO 7096 (2000)

The International Standard ISO 7096 (2000) is concerned with the measurement and evaluation of whole-body vibration transmitted through the seat to an operator during simulated vertical vibration. It defines nine classes of earth-moving machines, with each class grouping machines having similar vibration characteristics. These machine classes each have an associated input acceleration power spectral density (EM1 through EM9) defined in the standard. These spectra are representative of measured data from machines in each of the categories in severe but typical working conditions.



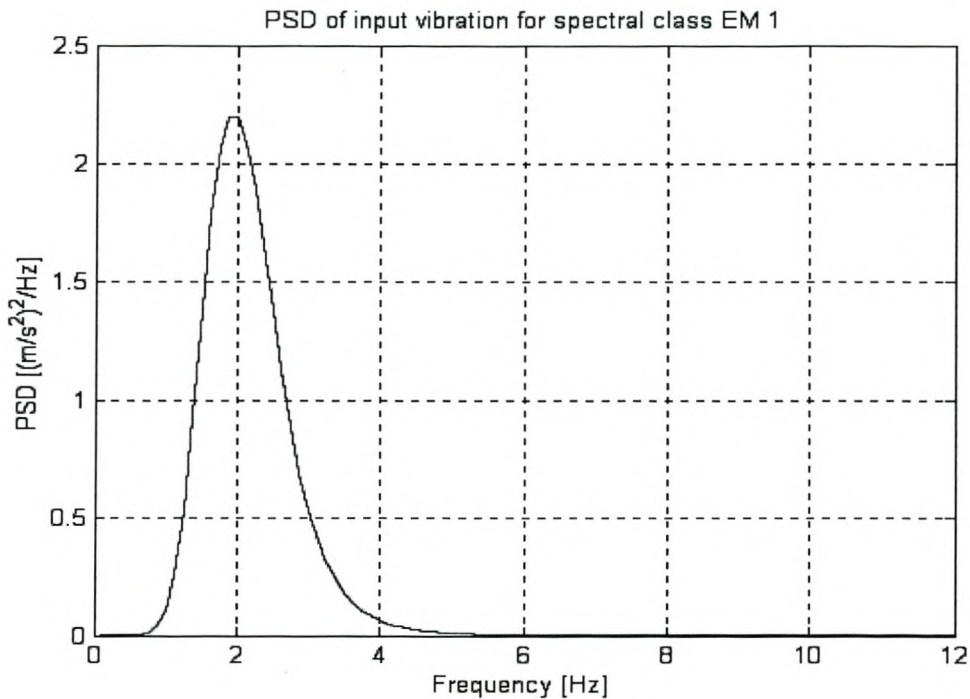
According to ISO 7096 (2000) the EM1 input spectral class, defined as “Articulated or rigid frame dumper > 4 500 kg” is the appropriate input spectrum to use to evaluate the suitability of a specific suspension seat for an articulated dump truck. Most of the energy of EM1 is concentrated between 1.5 Hz and 2.5 Hz as shown in Figure 3.6. The *r.m.s.* level of class EM1 is  $2.21 \text{ m/s}^2$ .

It is important to recognize that the seat evaluation method in ISO 7096 (2000) provides protection only for input vibration and shocks up to a specified level. The vibration levels in real life can be more severe than the input spectrum in the standard. It is therefore useful to compare the operational vibration data measured in a vehicle to the recommended input spectrum prescribed for testing seats. This is done primarily to aid optimal seat selection, as the input vibration, i.e. the vibration environment, significantly influences the vibration transmission in a seat.

The power spectral densities for the articulated dump truck’s operational vibration data (Figure 3.2) were compared with the EM1 spectrum. It is observed that whereas the power spectral densities for the vehicle vibrations describe frequency distributions that contain energy up to 25 Hz, EM1 only has energy in the low frequency range of 0.5 to 5 Hz. The un-weighted *r.m.s.* values for the operational vibration data are however comparable with the *r.m.s.* value of EM1. Vibration effects and vibration transmission through a seat are significantly influenced by the frequency content of a vibration signal. Therefore the EM1 spectrum may not be an adequate representation of the vehicle’s input vibration for typical mining operations in the South African industry.

On the other hand, the EM3 input spectral class, defined as “Wheel loader>4500 kg” may be an appropriate input spectrum to use to evaluate the suitability of a specific suspension seat for the three-wheeled logger. In this case, most of the energy of the input spectrum is concentrated between 1.5 Hz

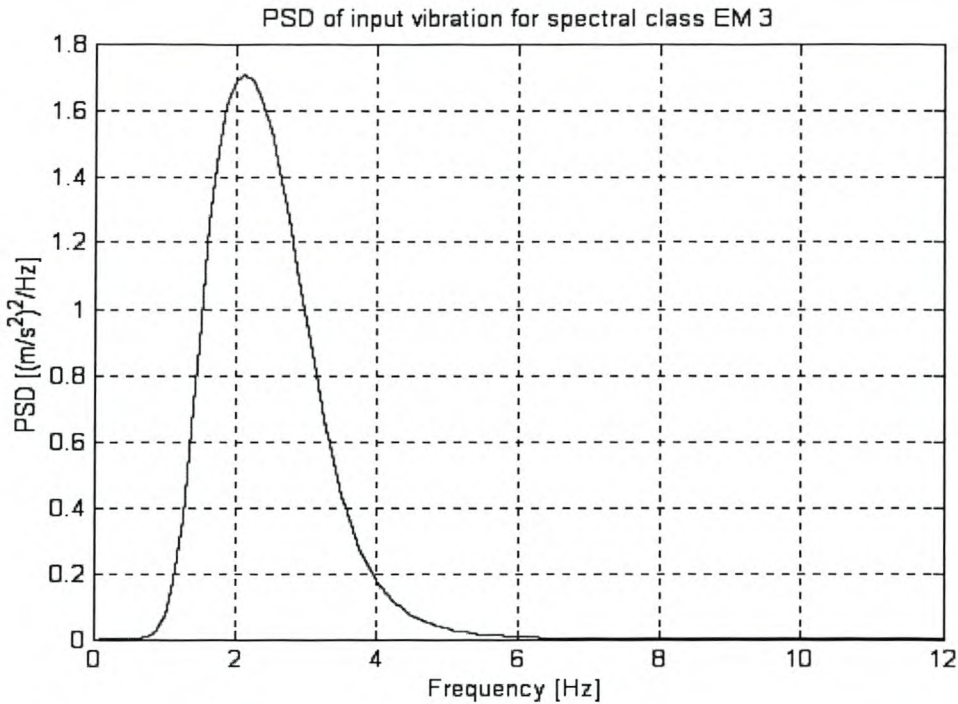
and 3.0 Hz as shown in Figure 3.7. The *r.m.s.* level of the input spectrum EM3 is  $1.71 \text{ m/s}^2$ .



**Figure 3.6** PSD of input vibration for spectral class EM1 according to ISO 7096:2000

The input acceleration power spectral density EM3 in Figure 3.7 was compared to the spectra for the measured vibration in the three-wheeled logger in Figure 3.4. It is evident in this case that the input spectrum recommended in ISO 7096 (2000) is more representative of the operational input than in the case of the articulated dump truck.





**Figure 3.7** PSD of input vibration for spectral class EM3 according to ISO 7096 (2000)

### 3.5. Conclusions

The vibration input spectrum is one of the factors that determine the effectiveness of a particular seat for whole-body vibration control in a specific industrial vehicle.

ISO 7096 (2000) has provided a set of guidelines for the laboratory evaluation of seats. The standard has defined nine classes of input spectra (EM1-EM9) for this purpose.

The frequency content and vibration level of the input vibration influence the vibration transmitted at the seat interface. The dynamic behaviour of seats is in most cases non-linear. The vibration transfer at the seat-person interface will differ greatly if the spectrum of vibration used in the laboratory tests is not a satisfactory representation of the measurements in the field (Griffin, 1990: p

398). The EM spectra are generalized and need to be compared to vibration data measured in vehicular operations in the industry under consideration.

Measurements taken in an articulated dump truck in a South African mining environment demonstrated that the ISO 7096 (2000) spectrum for this class of vehicle does not always adequately represent the operating conditions in this vehicle. However, measurements taken in a three-wheeled logger in a South African forestry environment demonstrated that the operating conditions in this vehicle may be adequately represented by the ISO 7096 (2000) spectrum for this vehicle.

It is known that seat vibration is sensitive to the frequency content of the vehicle vibration spectra. It may thus be necessary to augment the assessment of a suspension seat according to ISO 7096 with further seat testing using modified vehicle spectra having sufficient motion at all frequencies.

These results are based on measurements on one vehicle per spectral class. In order to establish the usefulness of the EM spectra for seat evaluation in the South African industry more vehicles need to be tested. It is also recommended that measurements are conducted to span more of the industries in South Africa.



## 4. Seat Transmissibility Measurements

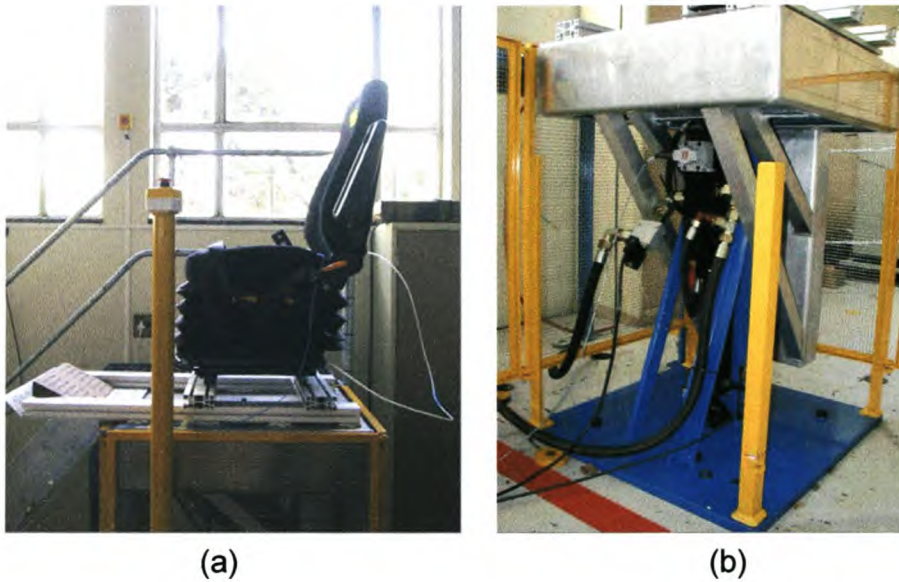
### 4.1. Experimental Set-Up and Procedures

Vertical seat transmissibility measurements were carried out on six suspension seats. The seats were from five different suppliers. The seats were all fitted with air-springs, and some of the seats had adjustable hydraulic dampers that could be switched “on” or “off”. The selection of seats is described in Table 4.1.

**Table 4.1 Description of seats tested**

Seat	Description
A	Air-suspension, no damper adjustment
B	Air-suspension, no damper adjustment
CD	Air-suspension, damper disengaged (off)
CE	Air-suspension, damper engaged (on)
DD	Air-suspension, damper disengaged (off)
DE	Air-suspension, damper engaged (on)
E	Air-suspension, no damper adjustment
F	Air-suspension, no damper adjustment

Tests were performed on the DSTF (Dynamic Seat Testing Facility) in the Structures Laboratory at Stellenbosch University. The DSTF is designed for the suitable and safe testing of seats according to various international standards. It consists of a man-rated, single axis platform, a servo-hydraulic actuator, and safety and control systems (Appendix B.1). The servo-hydraulic actuator has a usable stroke of 150 mm and can be used up to a frequency of 25 Hz. Several emergency measures have been installed to ensure safety, including one emergency switch within reach of the test subject (Figure 4.1).



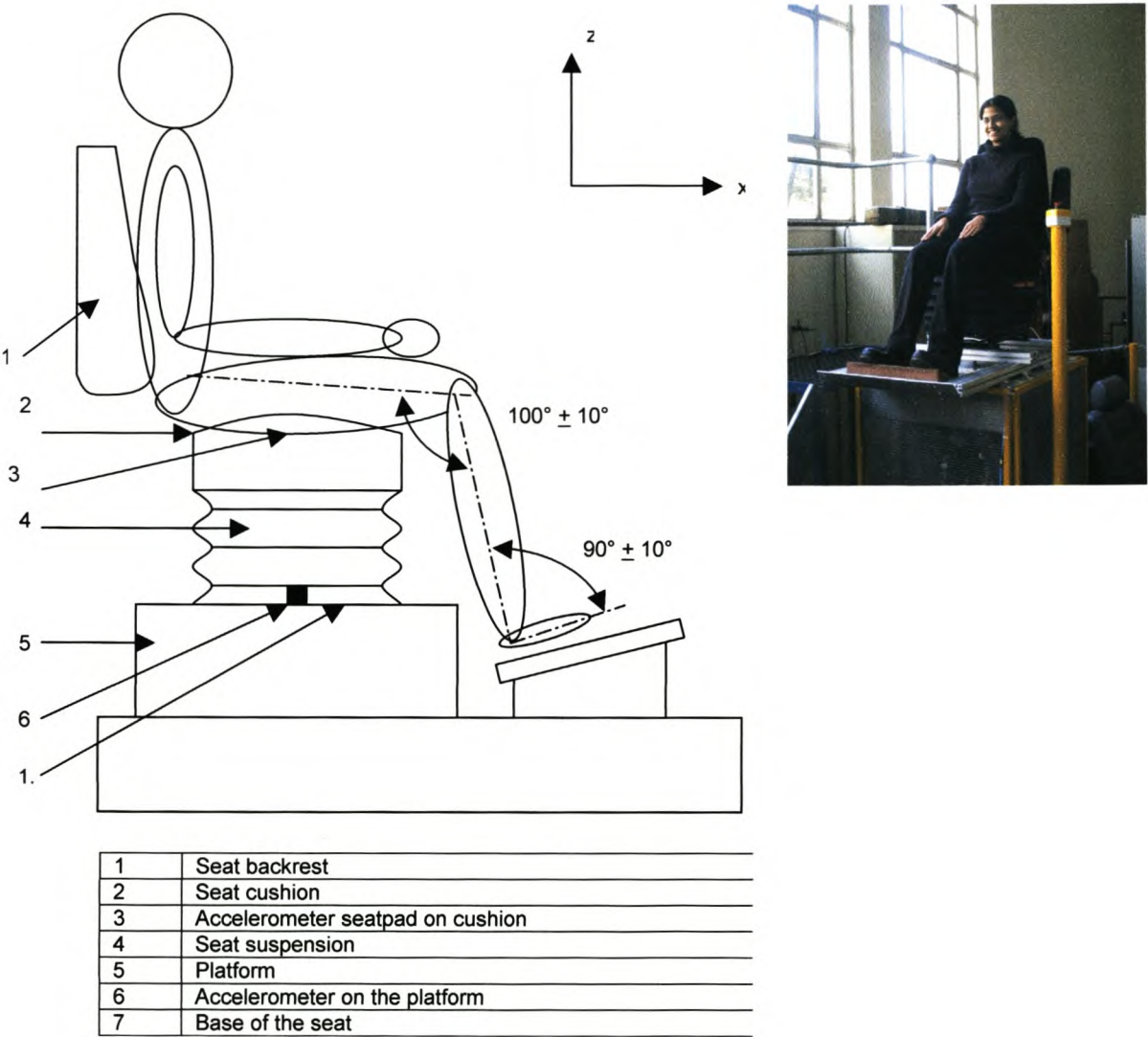
**Figure 4.1** The Dynamic Seat Testing Facility at Stellenbosch University: (a) man-rated platform with foot rest and emergency switch, with an attached seat, (b) servo-hydraulic actuator and platform support

The seats were all mounted rigidly to the platform of the DSTF. Each seat's backrest was approximately upright, inclined slightly backwards. The test subjects were requested to assume the recommended posture in ISO 7096 (2000) with their hands on their legs and with their feet flat against the footrest at the base of the simulated driving platform. The footrest was designed to accommodate the prescribed test posture. Some of the seats had vertical and lateral adjustments that were used by the test subjects to accommodate their stature. The test posture is illustrated in Figure 4.2.

Seat transmissibility is known to be dependent on the weight and size of the seat occupant. A range of test persons in different weight categories will thus have to be considered to obtain a satisfactory average transmissibility curve for each seat. Two weight categories of test subjects are suggested for seat transmissibility measurements in ISO 7096 (2000), namely the "light person" and the "heavy person". The "light person" is required to have a total mass of 52 kg to 55 kg, of which not more than 5 kg may be carried in a belt around the



waist. The “heavy person” is required to have a total mass of 98 kg to 103 kg, of which not more than 8 kg may be carried in a belt around the waist.



**Figure 4.2** Test person posture, ISO 7096 (2000)

Six subjects were selected for the seat transmissibility measurements, three in the “light person” category and three in the “heavy person” category. The subject characteristics are described in Table 4.2. Prior to the tests the subjects completed a consent form for participation in human vibration

experiments and were informed of their rights and the possible adverse affects of WBV exposure.

**Table 4.2** Characteristics of subjects used in seat characterisation

Subject no.	Gender (male/female)	Mass (with clothes) [kg]	Mass of weight belt [kg]	Total mass (as tested) [kg]	Height w/o shoes [m]
<b>Light Subjects (52-55 kg)</b>					
1	female	55.0	0	55.0	1.65
2	female	53.7	0	53.7	1.59
3	male	56.2	0	56.2	1.63
<b>Heavy Subjects (98-103 kg)</b>					
4	male	94.4	3.9	98.3	1.83
5	male	91.2	7.1	98.3	1.75
6	male	94.1	4.3	98.4	1.97

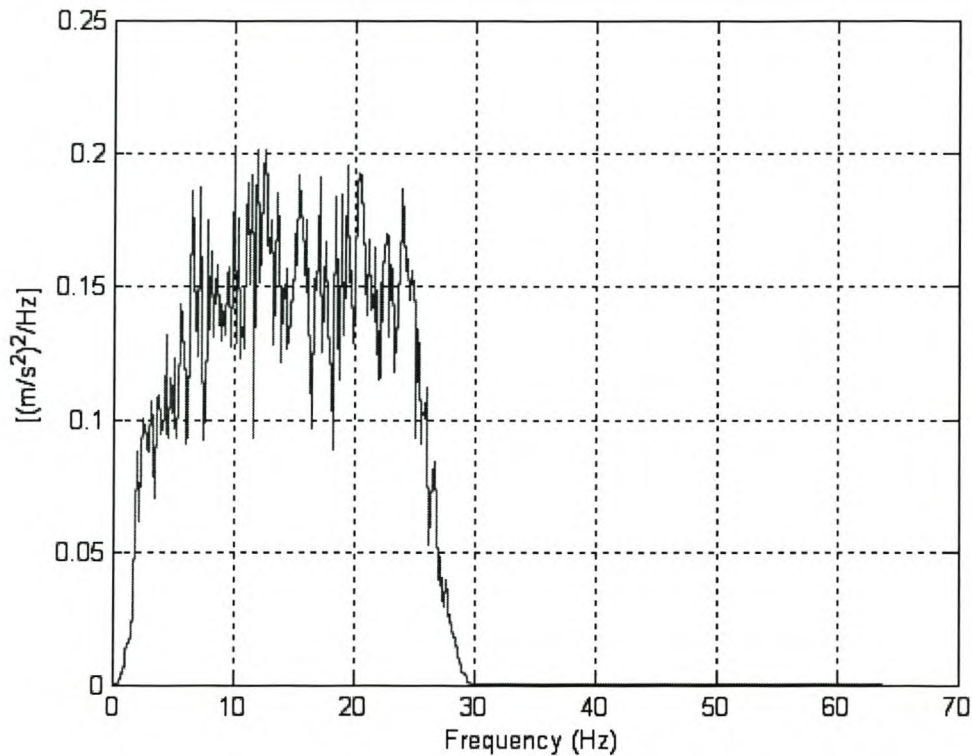
Two types of transmissibility measurements were conducted based on the type of vibration input. The first category used standardized broadband random vibration. Two levels,  $1 \text{ m/s}^2$  and  $2 \text{ m/s}^2$ , of vibration were used in this category to account for non-linearities in occupied seat systems, Griffin, 1990: p398. The broadband random vibration inputs had a frequency range of 0.5-30 Hz and provided reliable transmissibility estimates at all frequencies in this range. The power spectral density of the high level broadband vibration is illustrated in Figure 4.3.

The second category of transmissibility measurements used an approximation of the ISO 7096(2000) spectral class EM5 as input (Figure 4.4). Some high frequency energy was added to the original spectrum specified in the standard to improve the coherence (see Section 4.2) of the results.

The seats were conditioned to the weight of the test occupant by the person sitting in the seat for 5 minutes at the beginning of each test. A trial test was conducted to enable the seat to be conditioned further for the dynamic test.



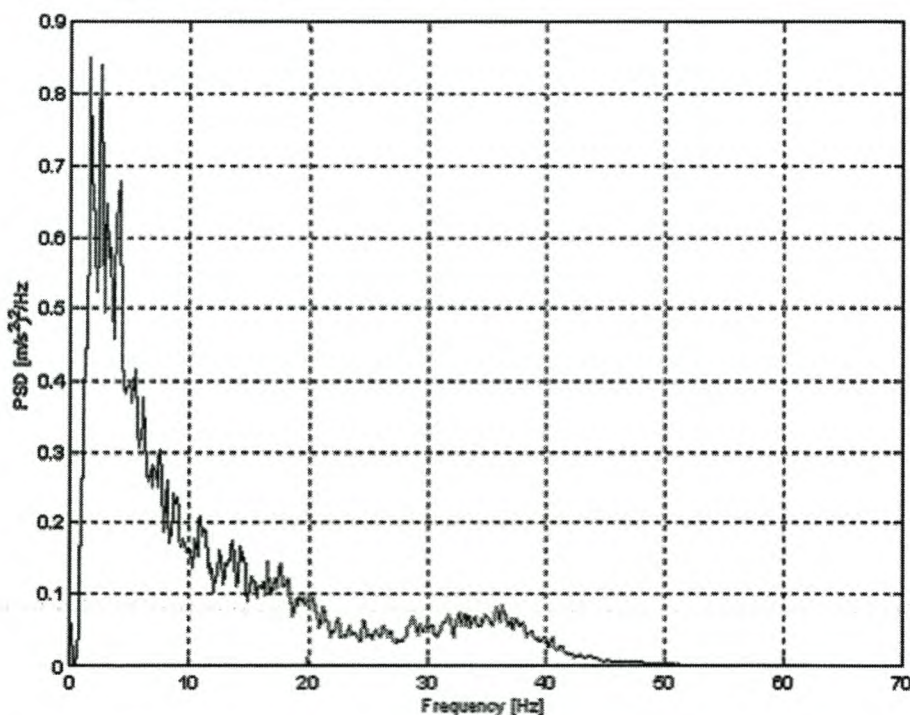
The room temperature during the experiment varied between 18 °C and 25 °C with the relative humidity between 32% and 51%.



**Figure 4.3** PSD of the high-level broadband input vibration spectrum (approximately 2.0 m/s<sup>2</sup> r.m.s.)

The transmissibility results were obtained from two channels of vertical acceleration measurements, at the base of the seat and at the seat-human interface. Vibration at the base of the seat was measured using a PCB Piezotronics single axis accelerometer (Model No. 353B33, SN 69345), secured by a screw-mount. A PCB Piezotronics seat pad with a tri-axial accelerometers conforming to ISO 10326-1 (1992) was used for the acceleration measurements at the seat surface (Model No. 356B40, SN 21385), refer Appendix B.1. The seat pad was taped to the seat surface with its centre approximately 128 mm from the seatback.

A commercial computer-based data acquisition and analysis system SigLab (version 3.2.6) was used for the acceleration signals and for displacement control along with MATLAB software programmes developed at Stellenbosch University for the control of the DSTF. Data was acquired for the duration of 204 seconds per measurement. The signals were low-pass filtered to prevent aliasing and sampled at 128 Hz. Only data up to 20 Hz was used for the transmissibility measurements. Analyses were subject to a low-frequency cut-off of 1 Hz due to accelerometer response.



**Figure 4.4** PSD of input vibration spectrum approximating EM5, ISO 7096(2000), measured on the platform (approximately  $2.0 \text{ m/s}^2$  r.m.s.)

## 4.2. Analysis (Bendat and Piersol, 1980a and b)

Transmissibility functions of the seats were calculated using the acceleration on the DSTF platform as the input and the acceleration on the seat surface as the output. The proportion of the output motion that is linearly correlated with the



input motion was only taken into account by the implementation of cross-spectral density functions. A block size of 1024, a sampling frequency of 128 Hz, and a frequency resolution of 0.125 Hz were used in the computation of the frequency response function,  $H(f)$ , which is given by:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)} \dots\dots\dots (4.1)$$

Where  $G_{io}(f)$  is the cross-spectral density of the input and output accelerations, and  $G_{ii}(f)$  is the power spectral density of the input.  $G_{oo}(f)$  is the power spectral density of the output. To aid with the interpretation of the frequency response function the coherence function,  $\gamma_{io}^2(f)$ , was determined by:

$$\gamma_{io}^2(f) = \frac{|G_{io}(f)|^2}{G_{ii}(f)G_{oo}(f)} \dots\dots\dots (4.2)$$

The coherence provides an estimate of the portion of the output motion that is linearly related to the input motion, and always lies in the range 0-1. For an ideal linear system with insignificant noise vibration the coherence will be unity at all frequencies, which implies that the output motion was caused by the input motion. Zero coherence will imply that the input and output are not linearly correlated. Poor coherence can be attributed to several reasons, some of which include the presence of noise, system non-linearity and the rapid change in the magnitude of the input or output spectrum with frequency.

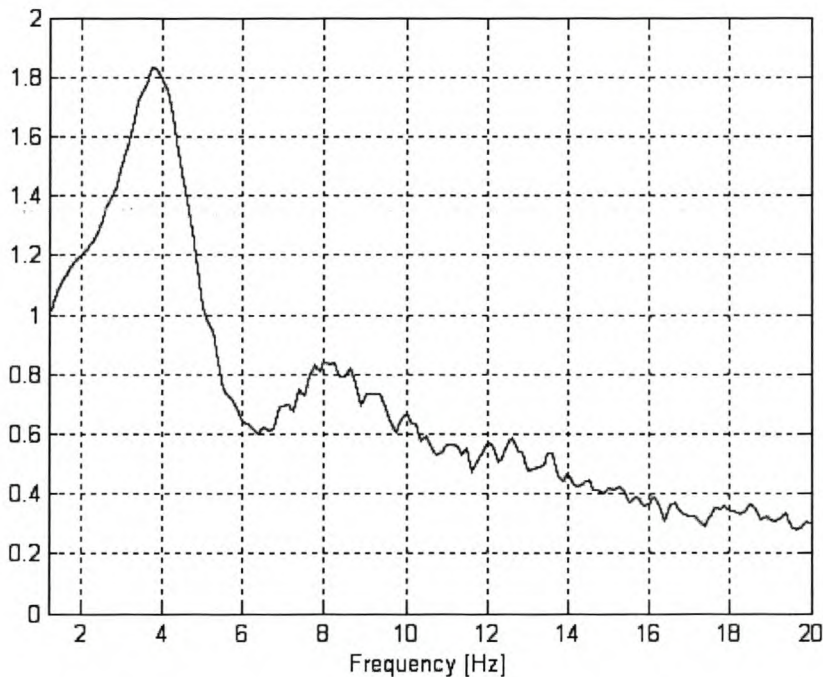
Transmissibility functions for the seats were obtained by taking the magnitudes of the frequency response functions at each frequency of the analysis spectrum.

These analyses were carried out in MATLAB; refer Appendix B.2 for more details.

### 4.3. Results and Discussion

Seat transmissibility functions were measured for two levels of broadband vibration inputs and for an approximate EM5 input for each suspension seat. These results are presented in Appendix B.3.

A typical seat transmissibility result for a broadband random vibration input is represented in Figure 4.5. The seat transmissibility curve is observed to start at 1.0. Primary resonance exhibits at approximately 4 Hz and is the dominant motion of the human (mass) on the seat (spring) although there is substantial coupling to the human body's inherent dynamics. A secondary resonance is observed around 8 Hz and is commonly believed to be associated with the upper legs' movement relative to the seat. These can be considered as general characteristics of occupied seat transmissibility for suspension seats (Griffin, 1990: p 399-401).



**Figure 4.5** A typical seat transmissibility result for the suspension seats (obtained using high level broadband vibration input and a “light” subject, ISO 7096, 2000)

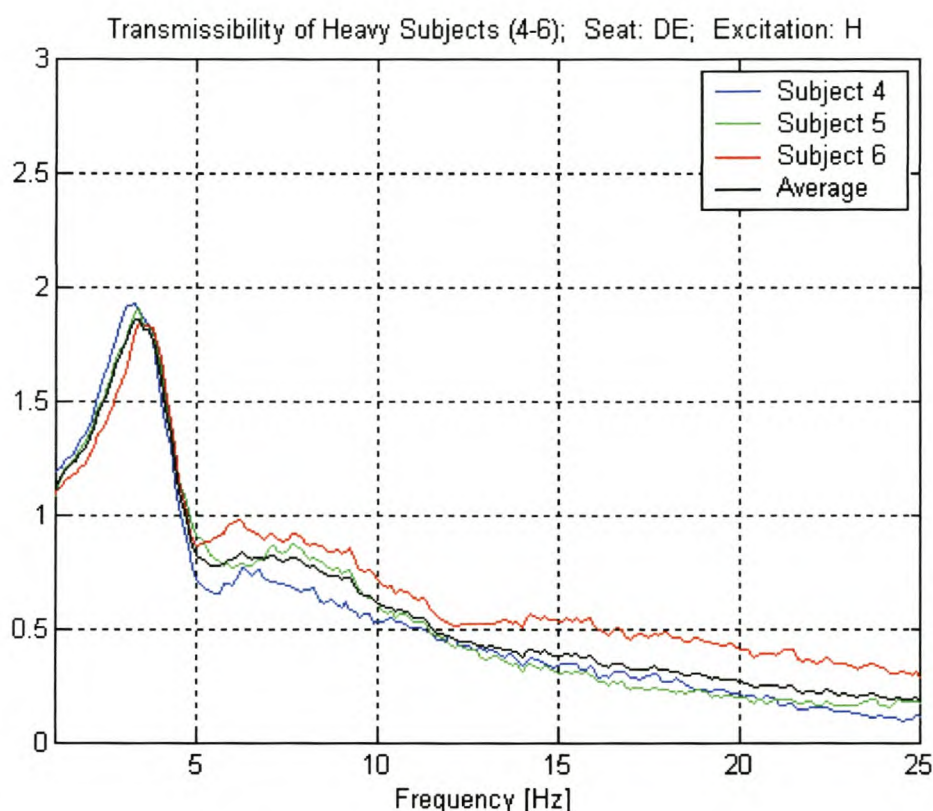


Average seat transmissibility functions were calculated for the two subject weight categories for each seat with the different input excitations. These were calculated by averaging the three individual transmissibility functions of the subjects representing each category. The individual transmissibility functions along with their average for each weight category for every seat at each input are presented in Appendix B.3. A sample of these results is represented in Figure 4.6. It depicts inter-subject variability within weight categories for the same seat and input excitation, which could be explained by the variation in human bio-dynamics between the subjects. The black curve represents the averaged transmissibility for this seat. The figure further illustrates that whereas the transmissibility function for subject 4 (blue curve) and subject 6 (red curve) exhibit secondary resonances in the 6-7 Hz frequency range the transmissibility for subject 5 (green curve) dips in this range. The average transmissibility on the other hand is relatively flat in the 6-7 Hz range. From this result it is clear that averaging transmissibility functions will have to be conducted with caution.

Previously it was stated that there is some dependence between subject weight and seat transmissibility and this dependence can be observed in Figure 4.7. The results for this seat (seat A) exhibit some peculiar behaviour in the seat transmissibility curves for the light persons, which have transmissibility greater than 1 for most of the frequency range of interest. This may be due to the fact that these subjects were too light to load the seats sufficiently, or that the seats were constantly bottoming out due to the ride height these subjects selected because of their smaller stature. In contrast, the transmissibility curves for the heavy subjects are more in line with what one would expect for suspension seat isolation, where the transmissibility dips below 1 after the primary resonance and remains there.

The averaged transmissibility graphs for all the seats are shown in Figure 4.8. From these graphs it is clear that seats B and C have low resonance peaks as

well as small transmissibility at higher frequencies and seem to be the more effective seats. Seat F has the highest resonance peak and average attenuation at higher frequencies and is incidentally also the seat that is currently installed in the articulated dump truck, one of the case studies in this project.

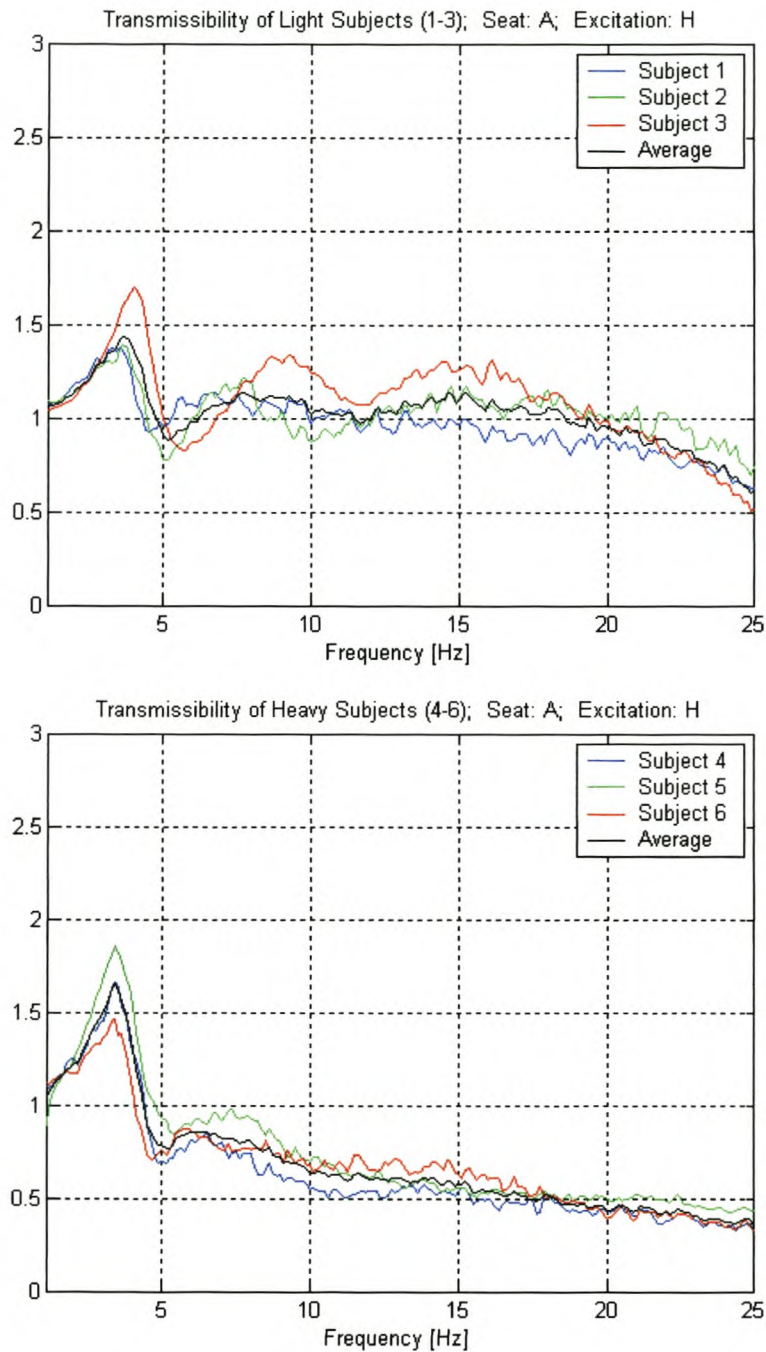


**Figure 4.6** Typical seat transmissibility results with high level broadband vibration input for the “heavy” subjects (ISO 7096:2000)

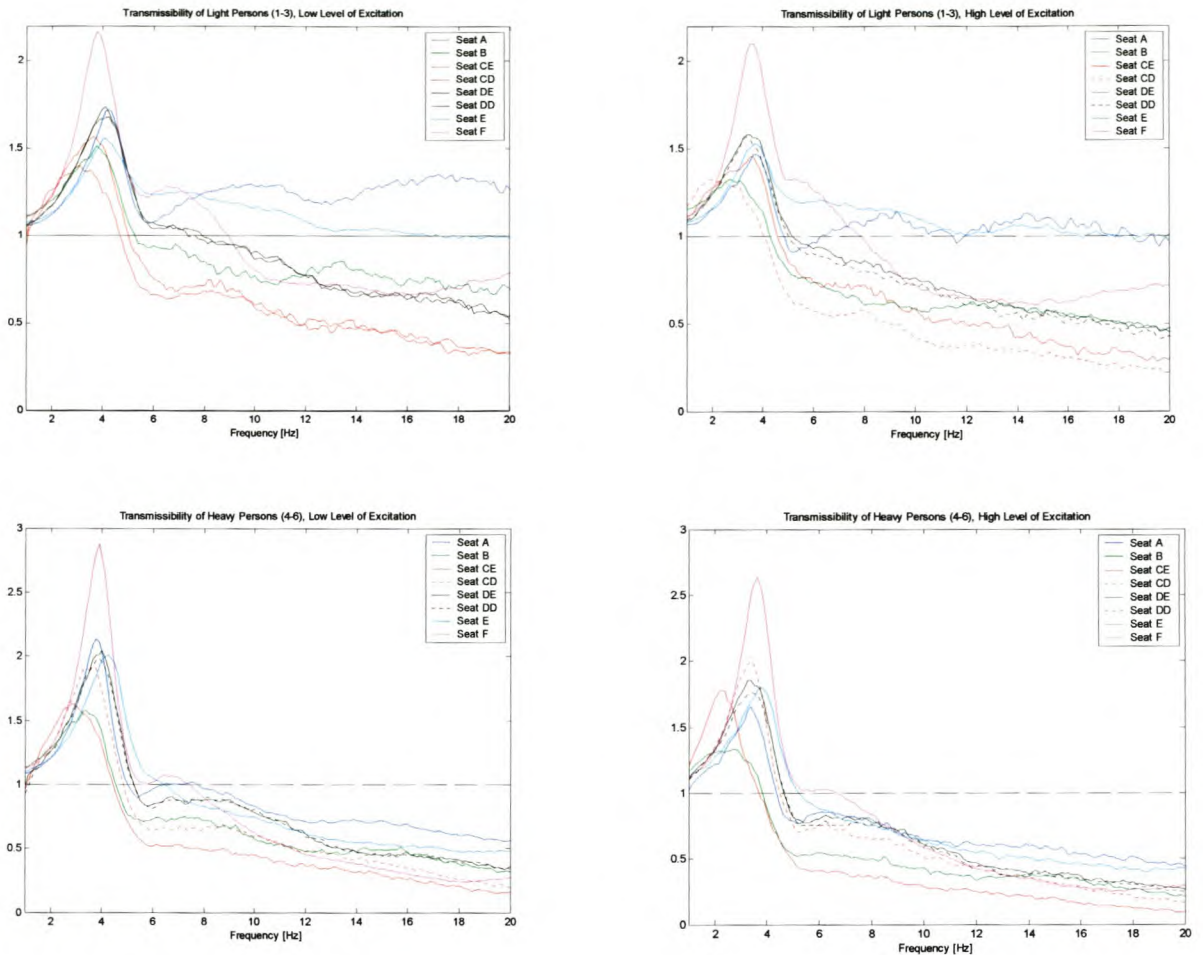
The results from the seat transmissibility measurements with the approximating EM5 (Figure 4.4) spectral input are also presented in Appendix B.3. Figure 4.9 illustrates a typical transmissibility obtained with this input and also shows how a coherency close to 1.0 is only maintained for frequencies up to 5 Hz. Conversely, the coherence functions for the broadband input transmissibility results in Appendix B.3 indicate that a coherency close to 1.0 tends to be maintained for most of the frequencies in the range 0-25 Hz. In a broadband



vibration input there is sufficient energy at all the frequencies under consideration, which results in the transmissibility functions having high coherencies for the entire frequency range.



**Figure 4.7** Comparison of seat transmissibility results for “light” and “heavy” subject groups with high-level broadband vibration input (ISO 7096:2000)

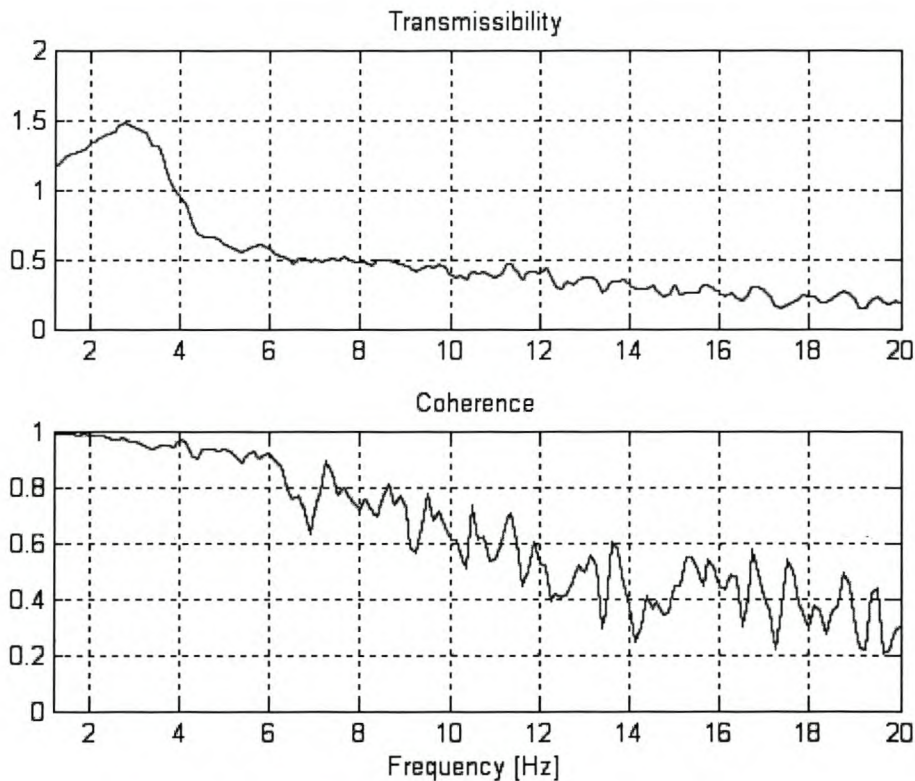


**Figure 4.8** Averaged seat transmissibility graphs with broadband vibration inputs

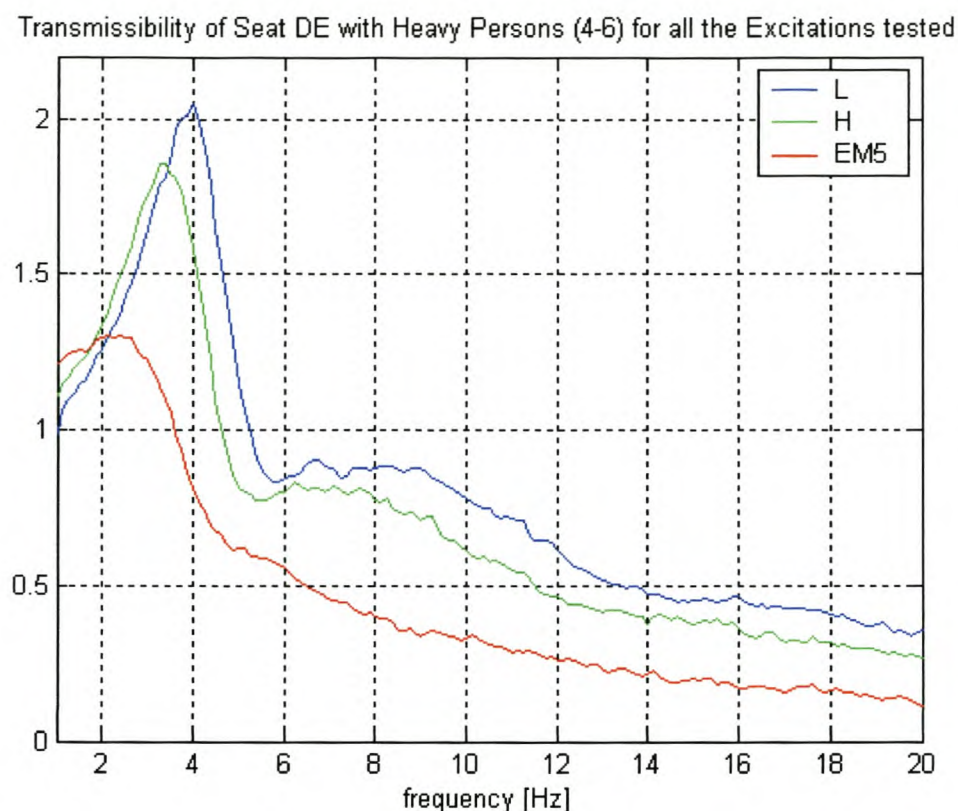
Suspensions seats are known to be non-linear and Figure 4.10 illustrates this phenomenon. It is observed that with the same seat and the same set of subjects the average transmissibility curve changes both in peak amplitude and resonance frequency with different input vibrations. The curves obtained for the “low level” (blue curve) and the “high level” (green curve) broadband vibration inputs describe how for similar input frequency contents the resonance frequency and resonance peak decrease with increasing magnitude (Griffin, 1990: p398-399). The results also depict that the low frequency spectral class input EM5 yields seat transmissibility with a lower resonance frequency, a lower peak and better attenuation at the higher frequencies, as



compared to the results with the broadband vibration inputs. Non-linearities are shown to play a significant role in the evaluation of the dynamic properties of seats and thus the type of input vibration needs to be described for valid comparisons to be drawn. This is in line with previous results published in Wu and Griffin (1996), and Stayner (1972). In Figure 4.10 L is the low level broadband vibration input (*r.m.s.*, 1 m/s<sup>2</sup>), H is the high level broadband vibration input (*r.m.s.*, 2 m/s<sup>2</sup>) and EM5 is the low frequency excitation (*r.m.s.*, 2 m/s<sup>2</sup>)



**Figure 4.9** A typical seat transmissibility result for the suspension seats (obtained using input spectral class EM5 and a “light” subject, ISO 7096, 2000)



**Figure 4.10** Comparison of transmissibility functions obtained using different input excitations for the “heavy” subjects (ISO 7096:2000)

#### 4.4. Conclusions

Seat transmissibility functions were measured for six suspension seats using two levels of broadband vibration inputs and a modified EM5 input.

Suspension seat transmissibility functions start at 1.0, exhibit primary resonance around 4 Hz or lower for large low frequency motions and exhibit a secondary resonance around 8 Hz.

Averaging transmissibility functions has to be approached with caution because the average of two extreme transmissibility functions may not reflect either transmissibility function accurately.



The seat transmissibility functions are influenced by the mass of the seat occupants. Light subjects may either be too light or may have builds that are too small to properly load suspension seats, which impedes the performance of the seats.

The current seat installed in the articulated dump truck is the worst seat in this range of seats according to the seat transmissibility data obtained in these tests.

The coherence functions for seat transmissibility measurements with the modified EM5 input are close to 1.0 only up to 5 Hz. When broadband inputs were used the coherence functions approached 1.0 for almost all the frequencies of interest.

Suspension seats are highly non-linear and exhibit shifts of up to 2 Hz in resonance frequency when inputs with dissimilar frequency distributions are used, especially in the lower frequency bands.

## 5. SEAT Value Estimation

### 5.1. Definitions (Griffin, 1990)

The *SEAT* (seat effective amplitude transmissibility) value is a number that is used to indicate the efficiency of the seat to isolate a person from vibration or shock. It is essentially a ratio of the vibration output on the seat surface to the vibration input at the floor and can be calculated using the following equation:

$$SEAT = \frac{\text{Vibration on the Seat}}{\text{Vibration on the Floor}} \dots\dots\dots (5.1)$$

Where, *Vibration on the Seat* and *Vibration on the Floor* can be represented by the weighted *r.m.s.* (root mean square) or *VDV* (Vibration Dose Value) of the measured signals. If the vibration consists of data with low crest factors it is adequate to use weighted *r.m.s.* values, else one has to use *VDVs* (refer definitions in Section 2.2). The weighted *r.m.s.* values can be computed in the frequency domain from the power spectral density functions of the input and output signals and the appropriate frequency weighting of human response to vibration, using the following equation:

$$SEAT = \left[ \frac{\int G_{ss}(f) W_i^2(f) df}{\int G_{ff}(f) W_i^2(f) df} \right]^{1/2} \dots\dots\dots (5.2)$$

Where  $G_{ss}(f)$  is the power spectral density of the seat vibration,  $G_{ff}(f)$  is the power spectral density of the floor vibration, and  $W_i(f)$  is the relevant frequency weighting function for the human response to the vibration in the position and direction that is of interest. (Note: the frequency weighting function  $W_i(f)$  above and below the line in Equation (5.2) always have to be the same).



The power spectral density of the seat vibration can be estimated from the seat transmissibility function,  $H_{fs}(f)$ , and the power spectral density of the floor vibration using:

$$G_{ss}(f) = G_{ff}(f) |H_{fs}(f)|^2 \dots\dots\dots (5.3)$$

Equation (5.2) is thus modified to Equation (5.4) and was used in the estimation of *SEAT* values from the available seat transmissibility functions and power spectral densities. The appropriate international standards weighting function for vertical vibration on the seat surface in the vertical direction is  $W_k(f)$ , as defined in ISO 2631-1997.

$$SEAT = \left[ \frac{\int G_{ff}(f) |H_{fs}(f)|^2 W_i^2(f) df}{\int G_{ff}(f) W_i^2(f) df} \right]^{1/2} \dots\dots\dots (5.4)$$

With the given definition, a *SEAT* value of 1.0 indicates that although the seat may have amplified the low frequencies and attenuated the high frequencies there is no overall improvement in the vibration exposure produced by the seat. A value of 1.0 for the *SEAT* value implies that the vibration exposure on the seat is equal to the vibration on the floor or the vibration on the top of a rigid seat. If the *SEAT* value is greater than 1.0, it indicates that the seat has amplified the vibration. A *SEAT* value of less than 1.0 implies that vibration attenuation is achieved, thus a desired criteria for seats. The vibration isolation capability of the seat is determined by the amount to which the *SEAT* value is less than 1.0.

## 5.2. ISO 7096 Spectral Analysis

ISO 7096 (2000) specifies that *SEAT* values be determined using the input vibration in one of the nine prescribed spectral classes (EM1 through EM9) for

earth-moving machinery. These spectra are representative of measured data from machines in each of the categories in severe but typical working conditions. The standard stipulates *SEAT* value limits for each machine class against which the suitability of seats in whole-body vibration isolation can be assessed. It is important to realize that these spectra contain shocks that may be less severe than the real operational vibration in the relevant vehicle. The seat selection criteria specified in the international standard should be applied with this in mind.

The power spectral densities for some of the input classes (EM1 and EM4) are limited to the low frequency range, which yield *SEAT* factors close to or slightly greater than 1 when performing the seat test. This is explained by good seats causing a slight increase in vibration at the low frequency range because of the primary resonance, whereas vibration in the higher frequency range, depending on the type of suspension, is significantly reduced. The low frequency range vibration input is justified by the importance of shock loads that require good damping performance.

In this project *SEAT* values were determined using ISO 7096 (2000) spectral inputs for four of the suspension seats used in the seat transmissibility measurements, namely seats B, C, D and F. The seats were evaluated for suitability in whole-body vibration reduction in two vehicles: an articulated dump truck and a three-wheeled logger.

Due to the non-linear characteristics of suspension seats (Figure 4.10) the transmissibility data obtained for the modified EM5 spectrum (Figure 4.4) was used to compute *SEAT* values with Equation (5.4). The modified EM5 spectrum is a reasonable approximation to the EM1 and EM3 inputs that could be simulated on the dynamic seat test facility without causing the testing system to become unstable. Only the heavy subjects in Table 4.2 were selected for these transmissibility measurements. According to current



anthropometrical data the 50<sup>th</sup> percentile South African male is expected to have a mass of 74 kg and a height of 1.77 m, RSA-MIL-STD-127: Volume 1 (1994). Drivers and operators of industrial vehicles are most likely, with a few exceptions, to fall in this anthropometric category. Light subjects defined in ISO 7096 (2000), on the other hand, can be no heavier than 55 kg, and are more likely representative of the Asian population included in an international standard. Measurements conducted on the heavy subjects alone should thus be sufficient for studies restricted to the South African industry.

### 5.2.1. Articulated Dump Truck: ISO 7096 Spectral Analysis

The EM1 input spectral class is the specified input spectrum for the estimation of *SEAT* values in articulated dump trucks, according to ISO 7096 (2000). The power spectral density function of this input spectrum is described in Figure 3.6.

*SEAT* values for the EM1 input class were calculated according to Equation (5.4) and are listed in Table 5.1. They were computed using the measured transmissibility data for the modified EM5 input spectrum. Both the average of the individual *SEAT* values obtained from individual transmissibility functions, and the *SEAT* value from the average transmissibility function were computed. From the data it seems that there is very little difference whether the individual seat transmissibility functions are used to compute the *SEAT* values, and then averaged, or when the *SEAT* values are calculated from the averaged seat transmissibility function.

ISO 7096 (2000) requires that *SEAT* values be calculated in the time domain, using the measured and frequency-weighted *r.m.s.* acceleration signals on the platform (EM1 to EM9) and on the seat cushion. Table 5.2 compares the results in Table 5.1 with *SEAT* value data obtained from a seat supplier using EM1 in the time domain.

**Table 5.1** Estimated *SEAT* values for EM1 input using transmissibility data with the modified EM5 spectrum as input

Seat	Subj 4	Subj 5	Subj 6	Average*	Ave. Transm.#
B	1.24	1.13	1.16	1.18	1.18
CD	1.36	1.42	1.33	1.37	1.37
<b>CE</b>	<b>0.81</b>	<b>0.91</b>	<b>0.84</b>	<b>0.85</b>	<b>0.85</b>
DD	1.00	1.00	1.02	1.01	1.00
DE	1.22	1.22	1.28	1.24	1.24
F	1.58	1.53	1.55	1.55	1.55

\* This average is calculated as the numerical average of the three preceding, individual *SEAT* values in each row.

# This value is obtained using the averaged transmissibility curve for light and heavy persons respectively.

**Table 5.2** Comparison of the *SEAT* values estimated from EM1 transmissibility data with the *SEAT* values measured in the time-domain

Seat	Estimated <i>SEAT</i> values from transmissibility data	Measured <i>SEAT</i> values from a seat supplier
CD	1.37	0.98
CE	0.85	0.77
DD	1.00	0.79
DE	1.24	0.79

The time-domain measurements of *SEAT* values for seat C and seat D are appreciably less than the *SEAT* values estimated from transmissibility data. It can therefore be concluded that *SEAT* values for suspension seats subject to large displacements at low frequencies cannot be estimated reliably from seat transmissibility functions, even if they were obtained with excitation levels comparable to the anticipated input. This is attributed to the non-linear behaviour of these types of seats when subjected to high levels of vibration (Wu and Griffin, 1996).

*SEAT* values were also calculated for the EM1 input using the measured transmissibility functions for the high-level broadband vibration input. These calculations were applied to all six seats and all the subjects described in Chapter 4 (refer *Appendix C*). It has been made clear that transmissibility



functions obtained with broadband vibration input cannot be used to estimate *SEAT* values for inputs where the vibration energy is concentrated between a few Hertz in the low frequency range, however the results are useful for comparing the seats that were tested. Table 5.3 summarizes the *SEAT* values that were computed with the transmissibility data. The *SEAT* values were computed using Equation (5.4) and the average transmissibility curve was used in each case. From the *SEAT* values computed with the high-level broadband vibration input transmissibility data in Table 5.3 it is observed that there are differences in the *SEAT* values between the light and heavy subjects as predicted by the differences in the measured transmissibility data. The seats are also seen to have varying effects in the two weight categories based on these estimations. For example, the best seat for the light subjects is seat A, whereas it is seat B for the heavy subjects. Seat F, as previously mentioned, is the current seat installed in the articulated dump truck studied in this project, and has the highest *SEAT* value in both weight classes, making it the worst seat for this application.

**Table 5.3** Estimated *SEAT* values for EM1 input using transmissibility data with the high-level broadband vibration input and the modified EM5 spectrum as input

Seat	Light subjects, broadband transmissibility (52-55 kg)	Heavy subjects, broadband transmissibility (98-103 kg)	Heavy subjects, EM5 Transmissibility (98-103 kg)
A	<b>1.21</b>	1.31	
B	1.25	<b>1.27</b>	1.18
CD	1.27	1.52	1.37
CE	1.30	1.55	<b>0.85</b>
DD	1.32	1.44	1.24
DE	1.33	1.48	1.00
E	1.25	1.38	
F	1.47	1.63	1.55

The *SEAT* values calculated the EM1 spectrum using the modified EM5 spectrum in Table 5.3 was computed with the average transmissibility curves

for the heavy subjects. A comparison between the *SEAT* values computed using the high-level broadband vibration input and the modified EM5 spectral input shows the differences to be significant, especially for seat C, emphasising the non-linearity of suspension seats.

The *SEAT* value limit for EM1 according to ISO 7096 is 1.1. Consider the *SEAT* value estimates obtained with the EM5 transmissibility data in Table 5.3. It is evident from the data that only seats C and D, with their dampers engaged, qualify as acceptable seats for the shock levels in EM1. These values are based on analysis in the frequency domain.

To provide a correct assessment of the seats in terms of the selection criteria in the specified international standard, there is a need for further tests to be conducted. These tests should include time domain measurements on the seat surface and the platform, with an EM1 input platform vibration. *SEAT* values should then be computed in the time domain using the relevant frequency weighted *r.m.s.* accelerations as in Equation (5.1). The current displacement limits on the dynamic seat testing facility used for these tests makes it impossible to produce the large displacements at low frequency required by EM1. The displacements required by the approximating EM5 spectrum (Figure 4.4) on the other hand could be reproduced on the platform.

### **5.2.2. Three-Wheeled Logger: ISO 7096 Spectral Analysis**

The appropriate input spectrum for the evaluation of seats in a three-wheeled logger according to ISO 7096 (2000) is the EM3 spectral class. Figure 3.7 describes the power spectral density function of this input spectrum.

The *SEAT* values for this spectral class were calculated using the measured transmissibility data obtained with the modified EM5 input spectrum. These



results are presented in Table 5.4. The seat transmissibility data for the heavy subjects were used in Equation (5.4) to estimate the reported *SEAT* values.

**Table 5.4** Estimated *SEAT* values for EM3 input using the transmissibility data with the modified EM5 input

Seat	Subj 4	Subj 5	Subj 6	Average*	Ave. Transm.#
B	1.16	1.03	1.07	1.09	1.08
CD	1.33	1.42	1.31	1.35	1.35
CE	<b>0.68</b>	<b>0.78</b>	<b>0.70</b>	<b>0.72</b>	<b>0.72</b>
DD	1.16	1.17	1.25	1.19	1.19
DE	0.90	0.91	0.94	0.92	0.91
F	1.60	1.54	1.55	1.57	1.56

\* This average is calculated as the numerical average of the three preceding, individual *SEAT* values in each row.

# This value is obtained using the averaged transmissibility curve for light and heavy persons respectively.

The ISO 7096 (2000) standard requires that the seats have *SEAT* values of less than 1.0 for the EM3 input. It is evident from the frequency domain estimates in Table 5.5 that only seats C and D, with their dampers engaged, qualify as acceptable seats for the shock levels in EM3. These observations are consistent with the *SEAT* value estimates for the EM1 input spectrum in Table 5.4. The correct evaluation of these seats for vibration control in the EM3 spectral class will have to be determined from time-domain measurements as in the previous case. As in the case of the EM1 spectral input analysis, seat F has the highest *SEAT* value.

It is necessary to note that all the suspension seats tested in this project will not conform to the basic dimensional characteristics of the cabin of the three-wheeled logger required for safe operation of the vehicle.

### 5.3. Real Road Data Analysis

#### 5.3.1. Articulated Dump Truck: Operational Data Analysis

Operational vibration data was obtained on an articulated dump truck to obtain power spectral densities that represent the input vibration spectrum at the base of the seat. The data was measured on the floor of the cab over a variety of road conditions (Section 3.1). The following operating conditions are represented by this data with the un-weighted *r.m.s.* levels stated in brackets:

- Vehicle stationary with engine idling ( $0.33 \text{ m/s}^2 \text{ r.m.s.}$ )
- Travelling at moderate speed on a tar road ( $0.69 \text{ m/s}^2 \text{ r.m.s.}$ )
- Travelling at moderate speed on a moderate gravel road ( $1.72 \text{ m/s}^2 \text{ r.m.s.}$ )
- Travelling at low speed on a bad gravel road ( $2.09 \text{ m/s}^2 \text{ r.m.s.}$ )
- Travelling at moderate speed on a corrugated gravel road ( $2.32 \text{ m/s}^2 \text{ r.m.s.}$ )

The *SEAT* values for the different seats for these road inputs were calculated according to Equation (5.4) using the averaged transmissibility functions for the heavy subjects with the high-level broadband vibration input. The results are listed in Table 5.5.

The power spectral densities of these operational vibration conditions (Figure 3.2) indicate that the frequency distributions of the signals are relatively broadband. In spite of this, the correct *SEAT* values can only be determined from more tests. These tests will require time domain measurements at the platform and the seat surface for the laboratory measurements. The measured floor vibration measurements for the vehicle will have to be constructed on the platform of the laboratory test facility in the time domain. The *SEAT* values are, however, useful for comparing the vibration levels in the different seats and operating conditions.



Table 5.5 shows that seat C maintains very low, if not the lowest, SEAT values for all the operating conditions. Seat C can thus be classified as the most appropriate choice of seat from the range for the control of whole-body vibration in the articulated dump truck. Seat F on the other hand has in most cases the highest SEAT value for the operating conditions represented, and can be classified as the worst choice of seat from the range. This observation is consistent with the transmissibility data in Chapter 4. As seat F is currently installed in the articulated dump truck the results indicate the need for proper seat selection in the South African industry.

**Table 5.5** Estimated SEAT values for operational vibration in the articulated dump truck using the transmissibility data with the high-level broadband input vibration

Seat	Light Persons (Subjects 1-3)				
	Idling	Tar road	Moderate Gravel	Bad Gravel	Corrugation
A	0.59	1.09	1.12	1.13	1.11
B	0.38	0.92	0.86	0.90	0.77
CD	<b>0.15*</b>	<b>0.83*</b>	<b>0.73*</b>	<b>0.80*</b>	<b>0.63*</b>
CE	0.18	0.98	0.88	0.93	0.75
DD	0.23	1.10	0.98	1.03	0.85
DE	0.24	1.07	1.01	1.06	0.88
E	0.75	1.20	1.19	1.20	1.14
F	0.34	1.39	1.23	1.27	1.06
Seat	Heavy Persons (Subjects 4-6)				
	Idling	Tar road	Moderate Gravel	Bad Gravel	Corrugation
A	0.30	1.07	0.96	1.00	0.85
B	0.16	<b>0.82*</b>	0.72	<b>0.78*</b>	0.62
CD	0.14	1.22	1.03	1.09	0.87
CE	<b>0.09*</b>	0.84	<b>0.70*</b>	0.81	<b>0.58*</b>
DD	0.19	1.18	0.99	1.05	0.83
DE	0.19	1.14	1.02	1.08	0.86
E	0.34	1.16	1.03	1.08	0.88
F	0.20	1.46	1.27	1.31	1.06

\* The lowest SEAT value for each operational condition.

### 5.3.2. Three-Wheeled Logger: Operational Data Analysis

Operational vibration data was collected for two operating conditions. Acceleration measurements were obtained for vibration on the floor beneath the seat in the driver's cabin. Data was analyzed using Equation (5.4) and the weighted floor vibration measurements. The following operating conditions were considered:

- Short run at slow speed on forest terrain with loading and unloading operations ( $1.36 \text{ m/s}^2 \text{ r.m.s.}$ )
- Long run at moderate speed on a corrugated road, unloaded ( $1.98 \text{ m/s}^2 \text{ r.m.s.}$ )

*SEAT* values were computed from average transmissibility functions for the heavy subjects obtained with the high-level broadband vibration input. The results are listed in Table 5.6. Broadband vibration input transmissibility data were used to maintain consistency with the analyses carried out for the articulated dump truck. However, the power spectral densities of the floor vibrations in the three-wheeled logger (Section 3.3) are concentrated in the low-frequency range, whereas the articulated dump truck has spectra (Section 3.2) with a more broadband frequency distribution. The three-wheeled logger thus has floor vibration that is better represented by the EM5 spectra than the broadband input vibration spectra used to compute the average transmissibility functions for the seats (Section 4.3).

From Table 5.6 it is evident that seat B is the most effective seat, in this range of seats, for whole-body vibration control in the three-wheeled logger. These results are consistent with the seat transmissibility data in Section 4.3, where seat B was observed to have a low resonance peak and small transmissibility at high frequencies.



**Table 5.6** Estimated *SEAT* values for operational vibration in the three-wheeled logger using the transmissibility data with the high-level broadband input vibration

Seat	Loading and Unloading	Long run , Unloaded
A	1.08	1.15
B	<b>1.01</b>	<b>1.11</b>
CD	1.21	1.32
CE	1.25	1.41
DD	1.20	1.25
DE	1.17	1.29
E	1.14	1.19
F	1.32	1.40

The current seat installed in the three-wheeled logger used in this investigation is a foam seat without any suspension. This case study also included vibration measurements on the seat surface of the foam seat in the vehicle. The actual *SEAT* values for the current seat installed for the given operational vibration conditions were calculated using the frequency weighted acceleration signals according to Equation (5.1). These results are listed in Table 5.7.

**Table 5.7** Measured *SEAT* values for the foam seat using acceleration time histories

Operation	Weighted <i>r.m.s.</i> accelerations at the seat base [m/s <sup>2</sup> ]*	Weighted <i>r.m.s.</i> accelerations at the seat interface [m/s <sup>2</sup> ]*	<i>SEAT</i> value
Loading and Unloading	1.16	1.33	1.12
Long run, Unloaded	1.22	1.52	1.19

Any further investigation into the use of suspension seats in the reduction of whole-body vibration to the operator of this vehicle should take the data in Table 5.7 into consideration. On the other hand suspension seats might not be suitable for this application.

## 5.4. Conclusions

*SEAT* values are in general computed from weighted *r.m.s.* values, when the vibration levels have low crest factors. These weighted *r.m.s.* values may be computed in the frequency domain from the power spectral densities of the input vibration and the transmissibility functions of seats.

*SEAT* values were calculated with the transmissibility data obtained for the broadband vibration inputs and also for the approximating EM5 spectral input.

Transmissibility data obtained with broadband signals cannot be used to estimate *SEAT* values for the low-frequency high-amplitude vibration inputs prescribed in ISO 7096. These data can however be used to compare different seats using the measured seat transmissibility functions as well as comparing the *SEAT* values for different measured road input data.

The suspension seat-person system is highly non-linear, thus *SEAT* values for suspension seats cannot be estimated reliably from seat transmissibility functions, even if they were obtained with excitation levels comparable to the anticipated input. *SEAT* values for the spectral classes in ISO 7096 (2000) will have to be determined from time domain data.



## **6. Seat Selection**

### **6.1. Development of Seat Selection Criteria**

Seat selection for whole-body vibration control in this project aims to minimize the transmission of vertical vibration to the driver of an industrial vehicle beneath the ischial tuberosities. The level of vibration transmitted to the driver of an industrial vehicle has been associated with:

1. Operator/driver characteristics
2. Operating conditions
3. Seat dynamic characteristics

A set of seat selection guidelines will assist manufacturers of industrial vehicles to promote safer working environments through reduced whole-body vibration control. A prerequisite for these guidelines is that they are practical and easily implemented.

#### **6.1.1. Operator/Driver**

The occupant of the seat affects the performance of the seat in attenuating vibration. Some of the characteristics of the driver that influence seat performance include posture, weight, build, gender, and fitness level (Stayner, 1972). The posture of the driver affects the seat transmissibility measurements by up to 10 per cent (ISO 7096, 2000).

ISO 7096 (2000) stipulates subject weight categories that cater for different countries and industries. To test seats to be fitted in a particular vehicle for use in the South African industrial environment it will be useful to select subjects that fit the most common profile of the drivers in the chosen industry. This

information can be obtained from anthropometrical data such as those presented in RSA-MIL-STD-127: Volume 1 (1994).

The testing of seats in this project used three subjects in each weight category. Using more than one subject in a given category will help eliminate error and any extreme outliers. Three subjects will help to distinguish which of the subjects display peculiar characteristics if there are significant discrepancies. The variation in human biodynamic behaviour can mean that there might be significant differences in the transmissibility functions between two subjects even when their weight, build, gender and fitness levels are the same. It is therefore suggested that at least three subjects are used in a specific weight category.

#### **6.1.2. Operational Vibration at Seat Base**

A seat is required to isolate the driver of a vehicle from the vibration on the cab floor. The usefulness of a seat in attenuating vibration to the driver of a vehicle is dependent on the level and frequency content of the floor input vibration.

The frequency content and level of the vibration on the cab floor of an industrial vehicle is determined by the vibration isolation provided by the vehicle and the operating conditions. The vibration isolation provided by the vehicle is defined by the tire suspension, the primary suspension, and the cab suspension. The type of operation, the speed of operation, and the terrain defines the operating conditions in a vehicle. It is therefore important to specify the vehicle as well as a set of industrial operating conditions for which whole-body vibration is required (Gillespie, 1992).

In order to obtain the cab floor vibration spectra in a vehicle, reliable vertical acceleration measurements of vibration at seat attachment points will have to be taken.



The vibration exposure time for the operation is used to evaluate the vibration exposure level. ISO 2631-1 (1997) provides ways of obtaining the equivalent 8-hour vibration exposure level.

### **6.1.3. Seat Dynamic Characteristics**

Seat dynamic characteristics can be described by transmissibility functions and *SEAT* values.

A seat will have different transmissibility functions depending on the type of input vibration. This is primarily due to the non-linearities in the seat (Wu and Griffin, 1996).

In order to obtain transmissibility estimates at all the frequencies a broadband frequency input vibration should be used in the laboratory measurements. It is necessary to report the non-linearity in seats and this is achieved if transmissibility measurements are carried out with two levels of broadband input vibration. The two vibration magnitudes can represent the lowest and highest encountered in the vehicle. A plot of the two transmissibility curves for the broadband input vibrations on the same axes can provide useful information. The average transmissibility curves obtained by averaging the individual transmissibility curves of the test subjects can be used in these plots.

The transmissibility data with broadband input vibration can only be used to compare different seats with each other. It is useful to plot the average transmissibility curves of all the seats on the same set of axes to aid visual inspection. Non-linearities in the seats prevent the use of these transmissibility data for determining any absolute values of peak transmissibility and attenuation efficiency.

The transmissibility curves will provide the relative peak transmissibilities and the relative attenuating performances at the higher frequencies (10-20 Hz) of

the seats. From published data and the seat transmissibility measurements in this project it might be reasonable to recommend that the seats have a peak transmissibility ratio of less than 2.5 when measured using a broadband vibration input (Griffin, 1990: p 400-401). The transmissibility ratios for the seats at frequencies between 10 Hz to 25 Hz can be recommended to be below 0.5 for the same vibration input.

It might also be beneficial to measure seat transmissibility using a spectrum from the operational vibration input. To determine the seat transmissibility reliably over the full range of the frequencies of interest it might be necessary to synthesise the vehicle vibration spectrum to have sufficient motion at all frequencies. Transmissibility measurements using the synthesised vehicle spectrum will provide a better indication of the resonance characteristics and the high frequency attenuation properties of the individual seats (Griffin, 1990: p 395).

*SEAT* values will supply the vehicle manufacturer with the isolation efficiency of the seats. The research in this project has shown that only direct measurements yield the absolute *SEAT* values. *SEAT* values estimated with transmissibility data can only be used to compare seats relative to each other.

Seat isolation efficiency for operational input vibration spectra need to be measured directly by simulating the vehicle vibration on the platform of the facility. This will assist in evaluating the usefulness of a seat in isolating the operator from hazardous operational vibrations. In the case of suspension seats ISO 7096 (2000) also requires the measurement of *SEAT* values using the applicable input spectral class (EM1 to EM9).

#### **6.1.4. Seat Selection Criteria**

The 8-hour equivalent vibration exposure level mainly validates seat selection. This vibration exposure level is required to conform to the requirements in the



European Directive 2002/44/EU. The seat with the lowest vibration exposure level that meets the requirements of the directive will qualify as the best seat. The directive has set a vibration action level of  $0.5 \text{ m/s}^2$  and a vibration exposure limit of  $1.15 \text{ m/s}^2$  for an 8-hour equivalent daily vibration exposure. For suspension seats the requirements in the European Directive are supplemented by the *SEAT* value acceptability requirements in ISO 7096 (2000). The seats are required to qualify as suspension seats according to this international standard in order to be selected as an acceptable seat for the vehicle.

One recommendation for seat selection is that the seat has relatively low *SEAT* values for the measurements with operational input vibrations. It is also recommended ensuring that the peak transmissibility of the seat is adequately off-set by the attenuation at frequencies above 10 Hz for the transmissibility functions obtained with the broadband input vibration spectra.

## **6.2. Seat Selection Guidelines**

The proposed guidelines for seat selection are presented in this section. The aim of these guidelines is to assist the manufacturers of vehicles with maintaining acceptable vibration exposure levels to the drivers.

The guidelines have been developed for the South African industry. It was seen as worthwhile for the guidelines to conform to the requirements in the European Directive 2002/44/EU. Although it is unlikely that similar requirements will be legislated in South Africa in the near future, the European Directive will result in new legislation in Europe and this will be seen as the standard by courts all over the world, including SA, and therefore workers may still use the European precedent in litigation against SA employers. In addition South African industrial vehicle manufactures have a substantial European

market, and the vehicles to be exported will have to meet the requirements in the European Directive.

It might be necessary for vehicle manufacturers to make provision for different seats to be installed for different operations. The mountings of seats need to be easily accomplished in order to cater for time management in productivity.

A copy of the “Design Guidelines for Seat Selection for Whole-Body Vibration Control” follows:



# **Design Guidelines for Seat Selection for Whole-Body Vibration Control in Industrial Vehicles**

## **1. Introduction**

The operators of industrial vehicles are exposed to low-frequency vibration levels that can adversely affect occupational health and safety. The seat is the last suspension mechanism that can isolate the driver. Selecting an appropriate seat has potential to significantly reduce whole-body vibration exposure levels to the operators. The efficiency of a seat in attenuating the vibration transmitted to the driver of an industrial vehicle is dependent on the type of vehicle and the type of operations carried out. Seats thus need to be selected in accordance with the dynamic characteristics of the vehicle and the vibration environment of the relevant industry.

## **2. General**

This document provides a method for selecting the best seat for the control of vertical whole-body vibration of the operator of an industrial vehicle between the frequencies 1 Hz and 20 Hz (as most industrial vehicles impart significant vertical vibration up to 20 Hz). The laboratory test conditions and test procedures of seat vibration are according to ISO 10326-1 (1992). The evaluation of suspension seats is according to ISO 7096 (2000). Whole-body vibration measurement and evaluation is according to ISO 2631-1 (1997).

The selection criteria aim to reduce the vertical vibration exposure level at the seat top for an equivalent 8-hour exposure period. The European Directive 2002/44/EU mandates a vibration action level of  $0.5 \text{ m/s}^2$  and a vibration exposure limit of  $1.15 \text{ m/s}^2$ , for an equivalent 8-hour exposure period. The

stipulations in this directive will be used to evaluate vibration exposure levels in the industrial vehicles.

This document contains guidelines for seat selection and does not contain details of procedures for vibration measurement and evaluation.

The factors that influence the vibration at the seat top of an industrial vehicle as:

- Input vibration at the base of the seat
- Seat occupant characteristics
- Seat dynamic characteristics
- Frequency weighting functions (according to ISO 2631-1 (1997))
- Vibration exposure time

The input at the base of the seat, the seat occupant characteristics, and the seat dynamic characteristics influence the vibration level at the seat top. The frequency weighting function and the exposure time are used to determine the whole-body vibration exposure level for an 8-hour exposure period from the seat top vibration.

This document contains guidelines for the listed factors that are considered to influence the vibration exposure level at the seat top, and concludes with a seat selection checklist.

The seat testing guidelines are dependent on the availability of an appropriate man-rated seat testing facility with a platform and servo-hydraulic actuator for the simulation of input vibration at the seat base. The seat testing equipment should comply with the requirements in the international standard ISO 10326-1 (1992).



### **3. Input Vibration at the Base of the Seat**

The input vibration at the seat base is determined by:

- Operational Input Vibration: the power spectral density function and/or time data of the operational vibration measured on actual vehicles in typical applications
- ISO 7096 (2000) Input Vibration: the power spectral density function of the relevant input spectral class (EM1 to EM9), for suspension seats, as defined in the standard.

#### **3.1. Operational Input Vibration**

The terrain over which the vehicle is driven and the tasks carried out determines the input vibration at the base of the seat. Therefore select the applicable **industry** and **operating conditions** for which a seat is required.

Measure the **vertical vibration at the seat base** for a selection of operating conditions. Acceleration measurements can be used to determine the vertical vibration at the seat base. It is recommended that at least three vertical acceleration measurements be taken in order to evaluate the pitch and roll motion of the vehicle vibration. The measurements of the vertical acceleration should be converted to a set of estimates of the vertical vibration at the seat base for each operation. It is sufficient to use rigid body dynamics for the estimation of the vibration input at the seat base.

Compute the root mean square values of the vertical vibration input estimates at the seat base for each of the operations. Determine the highest root mean square value acceleration (H) and the lowest root mean square value acceleration (L).

The **operational input vibration** is the average vertical vibration for the particular selection of operations. It is recommended that the operational input vibration is represented by time data and power spectral density functions.

The power spectral density functions of vehicle vibrations at the seat base in the vertical direction usually exhibit primary resonance between 1 Hz to 2 Hz due to the rigid body modes of the vehicle. Secondary resonances due to the wheel-hop modes can occur in the frequency range 10-15 Hz.

### 3.2. ISO 7096 (2000) Input Vibration

For suspension seat applications select the appropriate input spectrum (EM1 to EM9) for the applicable vehicle class, e.g. the EM1 input spectral class is defined for “Articulated or rigid frame dumper > 4 500 kg”. This spectrum is to be used to determine if the seat qualifies as a suspension seat according to ISO 7096 (2000).

The input spectra EM1-EM9 are based on measurements taken *in situ* on earth-moving machinery used under severe but typical operating conditions. The input spectra represent the vibration envelope of the vehicles within each class. The input spectra are represented by power spectral density functions.

## 4. Seat Occupant Characteristics

Seat transmissibility functions and *SEAT* values for the seats should be measured using at least **three** test subjects with characteristics similar to the characteristics of the average operator of the vehicle in the selected industries. Characteristics of the average operator will be determined from relevant anthropometrical data for the population segment that is most common to the drivers of the vehicle for the combination of operations and industries. The seat occupant shall be characterized by weight. It is also useful to record the height and gender of the subject.



## 5. Seat Dynamic Characteristics

The seat dynamic characteristics are described by:

- Seat transmissibility functions
- Seat Effective Amplitude Transmissibility (*SEAT*) values according to ISO 10326-1 (1992)

Seat transmissibility function and *SEAT* values can be measured on the seat test facility.

### 5.1. Seat transmissibility function

Two levels, at H and L, (see 3.1) of random broadband frequency vibration should be used as input to yield two transmissibility functions for each seat.

Obtain reliable transmissibility measurements with the two levels of broadband vibration input for all of the three test subjects. The individual transmissibility functions of the subjects obtained with the two broadband vibration inputs should be used to compute two average transmissibility functions for each seat. (Note: compare the average transmissibility curve with the individual transmissibility curves of the subjects and ensure that the average curve is a consistent representation.)

The pairs of transmissibility curves should be used to determine the **non-linear** effects of each seat.

The transmissibility functions of the seats should be used to compare the dynamic performance of all the potential seats for the vehicle. It is sufficient to use one set of the average transmissibility functions of the seats for the comparisons (in general the transmissibility results for the H level broadband vibration are used). The transmissibility at resonance, the resonance frequency

and the attenuation of vibration at high frequencies can be used to evaluate the most suitable seat from seat transmissibility functions.

## 5.2. Seat Effective Amplitude Transmissibility (SEAT) value

*SEAT* values can be used to indicate the efficiency of a seat in isolating the operator of a vehicle from the vibration on the floor of the cabin. *SEAT* values should be measured according to the measurement procedures in ISO 10326-1 (1992). The *SEAT* values can be measured from the root mean square values of the frequency-weighted (see Guideline No. 6) acceleration signals.

*SEAT* values are measured using the **operational input vibration**. Compare *SEAT* values obtained with the operational input vibration of the vehicle. Select the seats with the lowest *SEAT* values for the operational input vibration.

In the evaluation of suspension seats *SEAT* values should also be measured using the **ISO 7096 (2000) input vibration**. Assess the *SEAT* values of each seat according to ISO 7096 (2000).

## 6. Vibration Exposure Level

Vibration exposure levels should be calculated for an 8-hour equivalent day.

Frequency weighting should be used to determine the human response to vibration exposure. The frequency weighting should be according to ISO 2631-1 (1997) and is  $W_k$  for the vertical vibration at the top of the seat.

The typical vibration exposure time of each operation as observed in the selected industries shall be recorded in hours.

The frequency weighted acceleration for the equivalent 8-hour exposure period should be calculated according to ISO 2631-1 (1997).



## 7. Seat Selection Checklist

The seat selection criteria follow:

Seat Selection Criteria	Yes	No
Does the seat have acceptable transmissibility at resonance? (Transmissibility ratio below 2.5?)		
Does the seat have satisfactory attenuation at frequencies above 10 Hz? (Transmissibility ratio below 0.5?)		
Does the seat qualify as a suspension seat according to ISO 7096 (2000)?		
Does the seat have a relatively low <i>SEAT</i> value for the operational input vibration compared to other seats?		
Does the 8-hour vibration exposure level exceed the action level of $0.5 \text{ m/s}^2$ prescribed in the European Directive 2002/44/EU?		
Does the 8-hour vibration exposure level exceed the exposure limit of $1.15 \text{ m/s}^2$ prescribed in the European Directive 2002/44/EU?		

A block diagram describing seat selection is located in the Appendix.

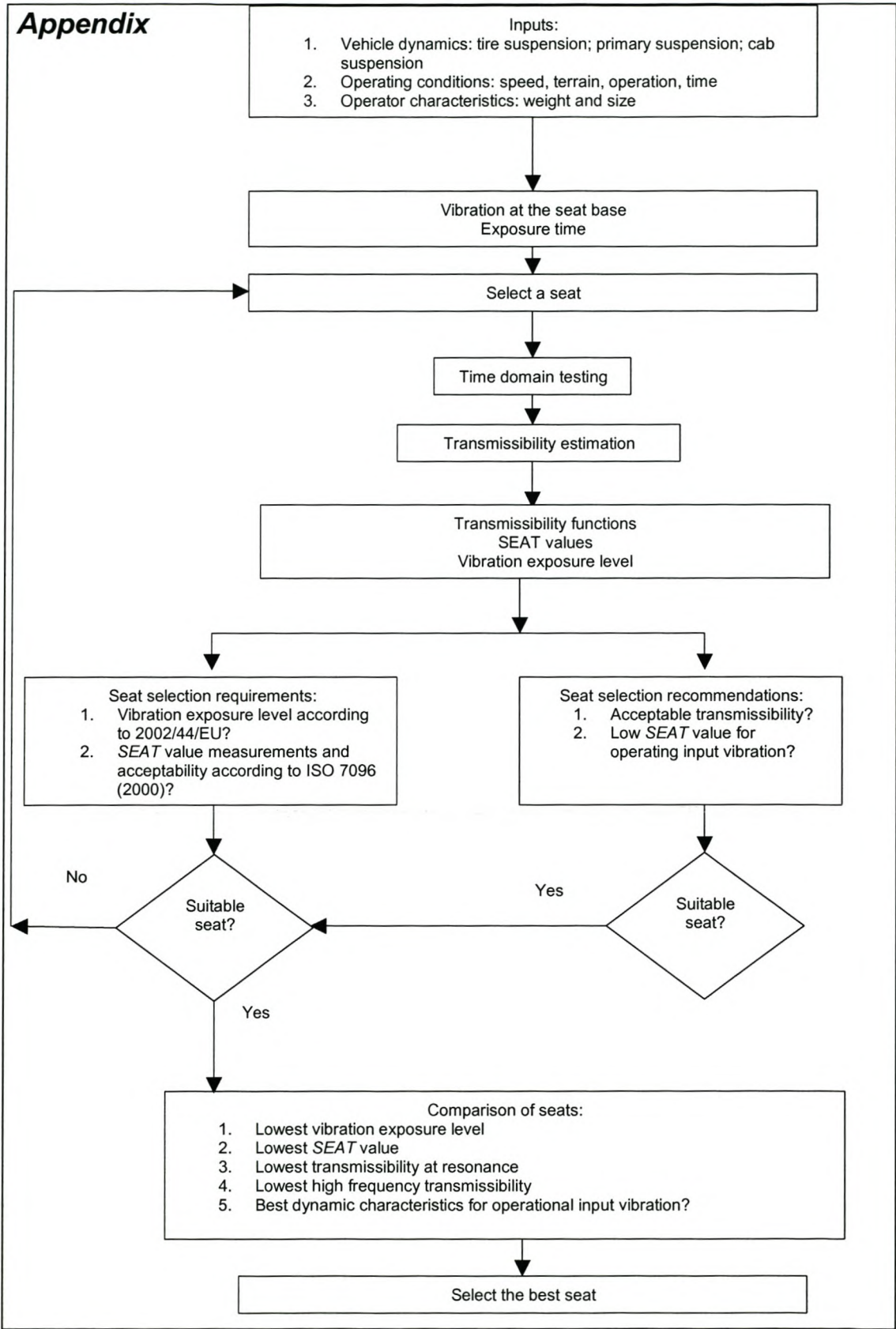
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## **7. Conclusions and Recommendations**

### **7.1. Introduction**

The primary objective of the thesis was to help reduce whole-body vibration exposure in the South African industry (mining, agriculture, forestry, and civil construction) through the proper application of seating. The secondary objective was to help create a database of road vibration affecting seat selection in the South African industry.

This study was approached through the development of suitable seat testing methods, seat vibration analysis procedures and seat selection criteria based on type of vehicle and type of vibration environment. The outcome of the research is a set of design guidelines for seat selection for whole-body vibration control in industrial vehicles.

The research procedure involved the testing and analysis of six suspension seats from five different manufacturers according to the International Standards ISO 7096 (2000) and ISO 2631-1.

Vehicle vibration measurements were carried out in an articulated dump truck and a three-wheeled logger for typical operating conditions. The vehicle vibration measurements attempted to quantify examples of the operating conditions in the South African industry.

### **7.2. Conclusions**

The main conclusions of this project are as follows:

- **It is necessary to supplement the suspension seat evaluation according to ISO 7096 (2000) with seat testing using operational input spectra.**

The power spectral density functions of the operational vibrations at the seat base of an articulated dump truck and a three-wheeled logger were compared with the relevant ISO 7096 (2000) spectra. The comparisons revealed significant differences in the frequency contents of the operational spectra of the articulated dump truck and the relevant EM1 spectrum. The estimated vibrations at the seat base for operations in the three-wheeled logger had less significant differences when compared with the relevant EM3 input spectrum. The frequency content of a spectrum is known to significantly influence seat performance. It is thus necessary to carefully define the selection of operations for which whole-body vibration control through seating is required.

- **The evaluation of seat vibration should be carried out with at least three subjects in each weight category.**

ISO 7096 (2000) defines two subject weight categories, a light subject has a mass of 52-55 kg and a heavy subject has a mass of 98-103 kg. Although some of the transmissibility measurements involved the testing of three subjects per weight category, the “light subjects” may have been too light to load the suspension seats properly. Results also indicated that there is inter-subject variability in the transmissibility curves with the subjects within the weight categories. Human bio-dynamics can vary significantly from person to person and is one explanation for the inter-subject differences in transmissibility functions when the subjects have similar weights and builds. ISO 7096 (2000) stipulates that at least one subject in each weight category be tested to evaluate suspension seats. This research points to the need for at least three subjects in each weight category to be tested to ensure that the test subject is the average rather than the exception.



- **Suspension seats are highly non-linear.**

Three input vibrations were used for the transmissibility testing of seats, two levels of broadband input vibrations and a modified EM5 input spectrum. Suspension seats are known by previous research to have significant non-linearities; the extent of these non-linearities was highlighted by the transmissibility data obtained with the three vibration inputs. Changing the input from broadband frequency vibration to the low-frequency vibration EM5 can cause a shift in the resonance frequency up to 3 Hz.

- **In order to obtain reliable seat transmissibility at all the frequencies under consideration it is important to use a random broadband frequency vibration input.**

The transmissibility functions measured with the modified low-frequency vibration input EM5 had acceptable coherence (close to 1.0) only up to 5 Hz, while with the broadband inputs the coherence was close to 1.0 up to 20 Hz.

- ***SEAT* values for suspension seats that are subjected to large displacements at low frequencies cannot be reliably estimated from seat transmissibility functions, even if they were obtained with an input vibration that is similar to the anticipated input vibration.**

*SEAT* values were estimated from the seat transmissibility data in the frequency domain. The *SEAT* values for the EM1 input, representing the vehicle class for articulated dump truck, were computed using the transmissibility data measured with the modified EM5 input spectrum for the suspension seats. The estimated *SEAT* values for the EM1 input were compared with *SEAT* values from a seat supplier that were measured in the time domain for seats C and D. The measured *SEAT* values were appreciably less than the estimated *SEAT* values.

- **There is need for the proper selection of seats in the South African industry.**

All of the measured transmissibility data and the estimated SEAT value point to the fact that the current seat (seat F) installed in the articulated dump truck, studied in this project, is the worst of the six seats for isolating the operator from hazardous vibrations. Seat B on the other hand may be more effective in controlling whole-body vibration exposure to the driver of an articulated dump truck.

### **7.3. Recommendations for Future Work**

The work undertaken in this project confirms for industrial vehicles what was recommended by Paddan and Griffin (2001) for commercial vehicles, that seats should be considered a major means of reducing exposure to whole-body vibration. It is recommended that a proper seat selection process is observed in order to minimize the whole-body vibration exposure and ensure that the seat functions as a vibration isolator and not a vibration amplifier for the operating conditions of the vehicles.

The seat selection criteria presented here have been based on the laboratory testing of suspension seats and the field-testing of two industrial vehicles. Due to the dependence of the exposure levels of whole-body vibration to the driver characteristics of an industrial vehicle on the vehicle dynamics, the seat dynamics and the operating conditions the following recommendations for future work are proposed:

- A comprehensive epidemiological survey of the whole-body vibration exposure and associated health risks in the industrial vehicles representative of the vast South African industry



- The measurement of the dynamic performance of non-suspension seats as well as suspension seats of these vehicles under different operating conditions
- Measurements of whole-body vibration through backslap, etc. as it is possible for vibration in the vertical axis at the seat input to produce vibration in another axis on the seat.
- Seats are investigated for shock loading and dynamic loading representative of the operating conditions.
- The investigation of the effects of damping on the dynamic performance of seats

A seat's characteristics can change during its lifetime. It might be beneficial to study or carry out investigations on the dynamic performance of seats over the general lifespan of the vehicles.

## **7.4. Summary**

Current seat selection for whole-body vibration control in the vehicles in the South African industry needs to be subjected to a set of seat selection guidelines in order to ensure that drivers are adequately protected from harmful vibrations, improve productivity in industry, and ensure that the vehicles are marketable in Europe. A preliminary set of design guidelines to seat selection for the control of whole-body vibration has been presented in this project. These guidelines were based on the testing of the six suspension seats studied in this project and literature survey. Future work should include comprehensive measurements of the operating vibration conditions in the South African industry.

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## Appendix A: Vehicle Vibration Measurements

### A.1. Industrial Vehicles



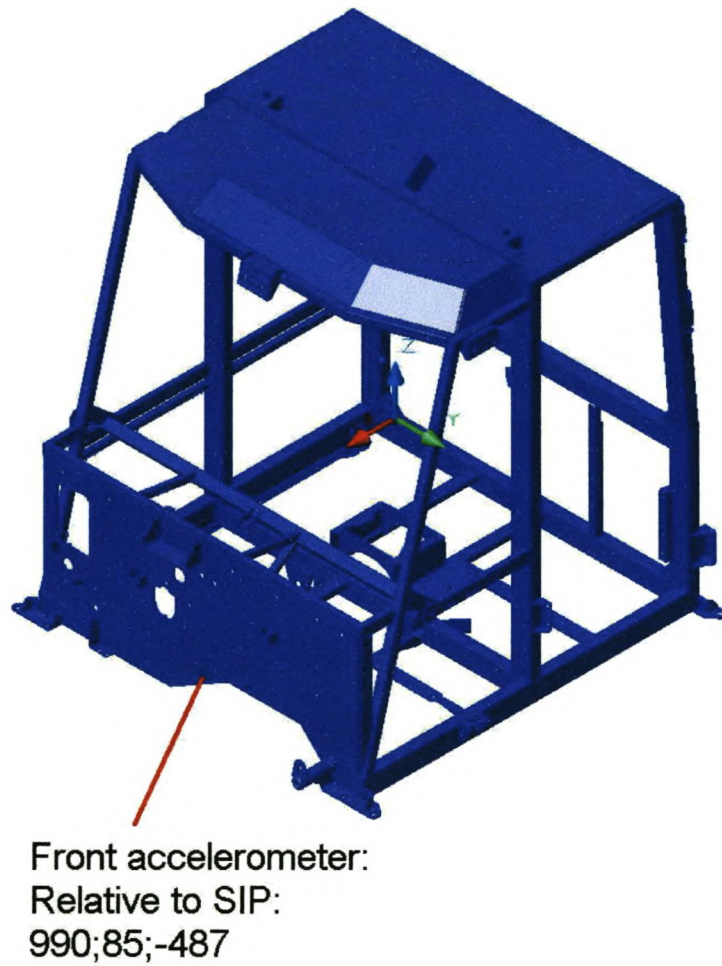
**Figure A.1** An example of an articulated dump truck



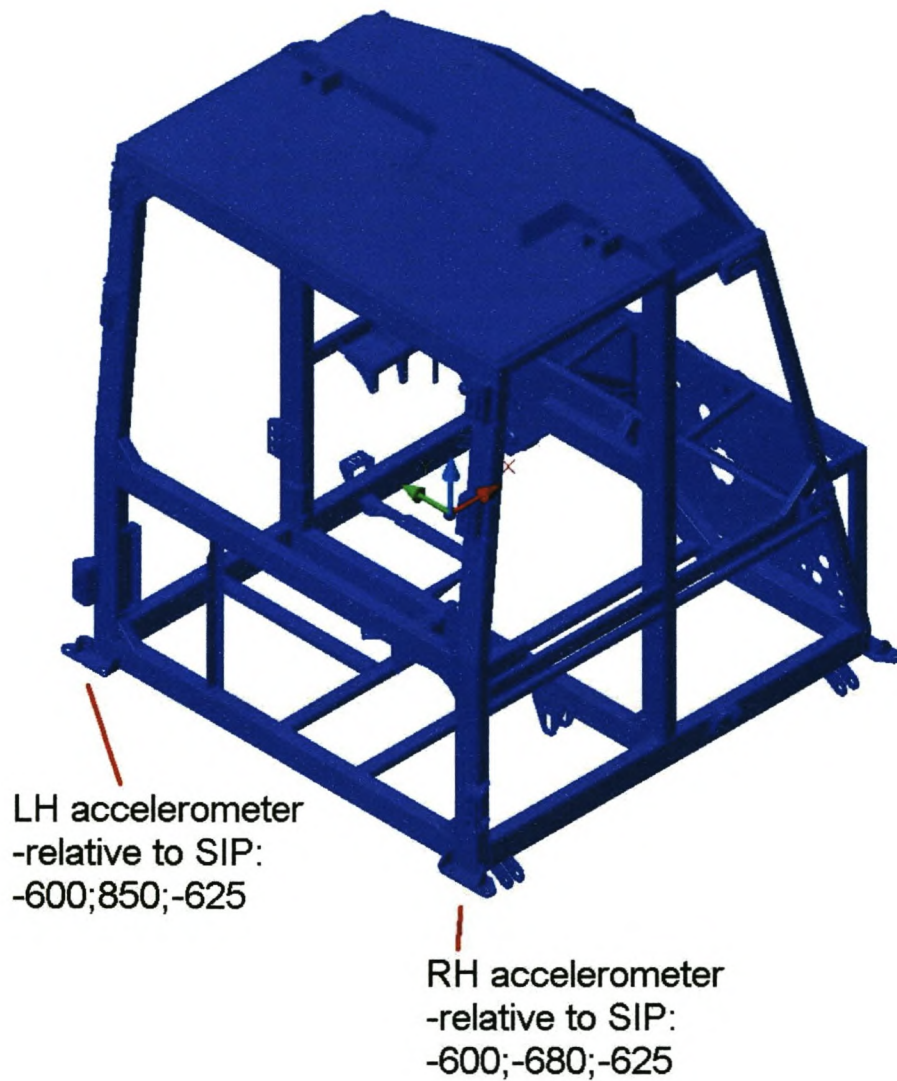
**Figure A.2** An example of a three-wheeled logger



## A.2. Articulated Dump Truck Measurements



**Figure A.3** 3-D drawing of the cabin of the Bell ADT D40 describing the front transducer mounting position used in the vibration tests



**Figure A.4** 3-D drawing of the cabin of the Bell ADT D40 describing the rear transducer mounting positions used in the vibration tests

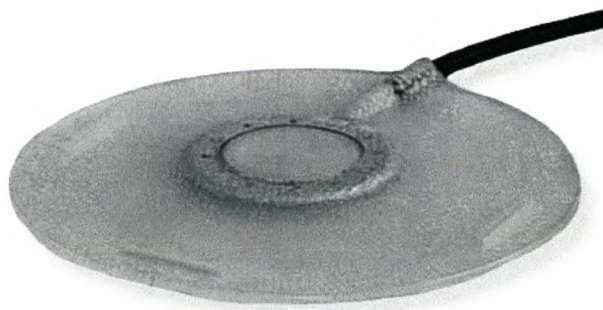


## Appendix B: Transmissibility Measurements

### B.1. Experimental Set-Up and Procedures



**Figure B.1** Transmissibility measurements set-up with the DSTF, the controller, SigLab, computer and monitor



**Figure B.2** An example of a tri-axial seat pad accelerometer (<http://www.scantekinc.com/datasheets/kb103sv.pdf>)

## B.2. Seat Transmissibility Measurement M-Files

MATLAB was implemented in the acquisition, analysis and processing of data for the seat transmissibility measurements from the Dynamic Seat Testing Facility (DSTF).

**Table B.1 M-Files implemented in the seat transmissibility measurements\***

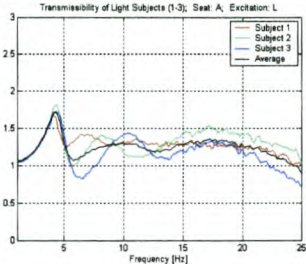
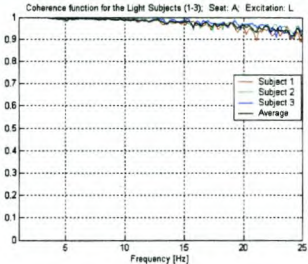
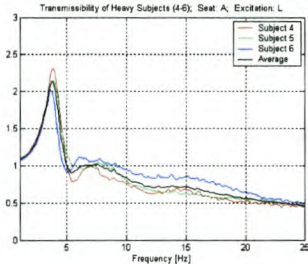
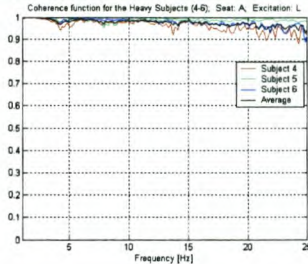
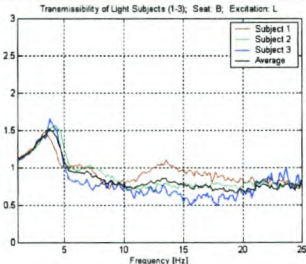
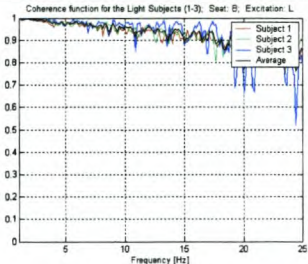
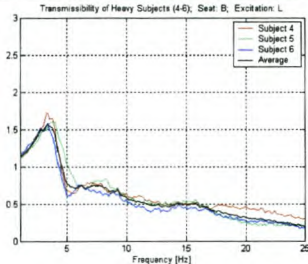
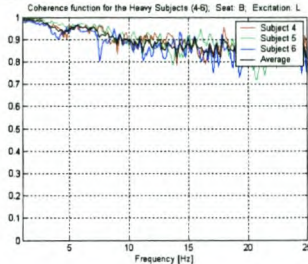
M-File	Type	Description
Transmissibility.m	Measurement and Analysis	Main Program for Seat Transmissibility Measurements
xfer_meas.m	Measurement and analysis	Determines the transfer function of the DSTF
mypsd.m	Analysis	Provides the Power Spectral Density (PSD) estimate
compute.m	Data processing	Provides transmissibility plots and SEAT values for the acquired data
wk.m	Data processing	Frequency weighs the acceleration signals obtained for seat transmissibility

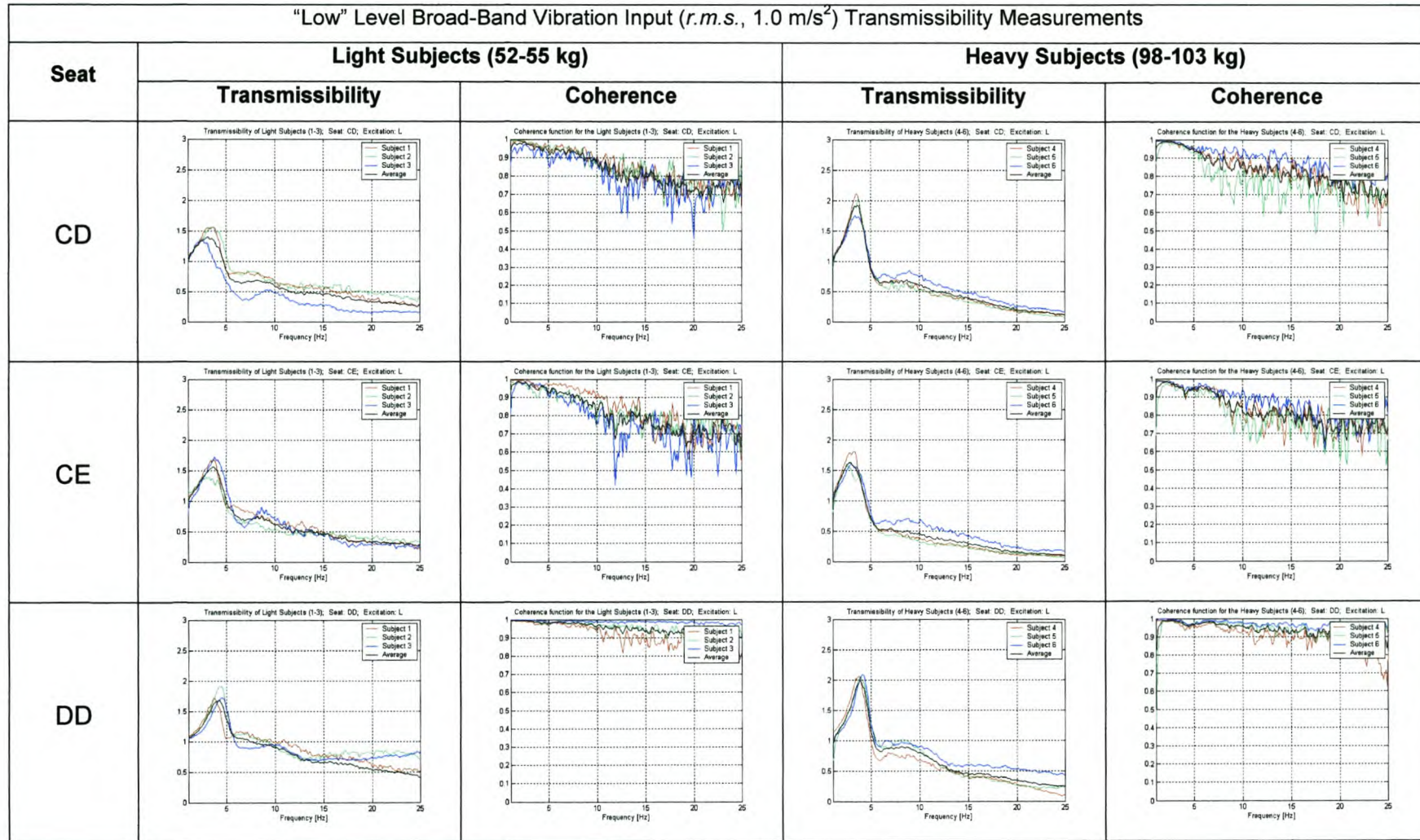
\*These files are available on request.



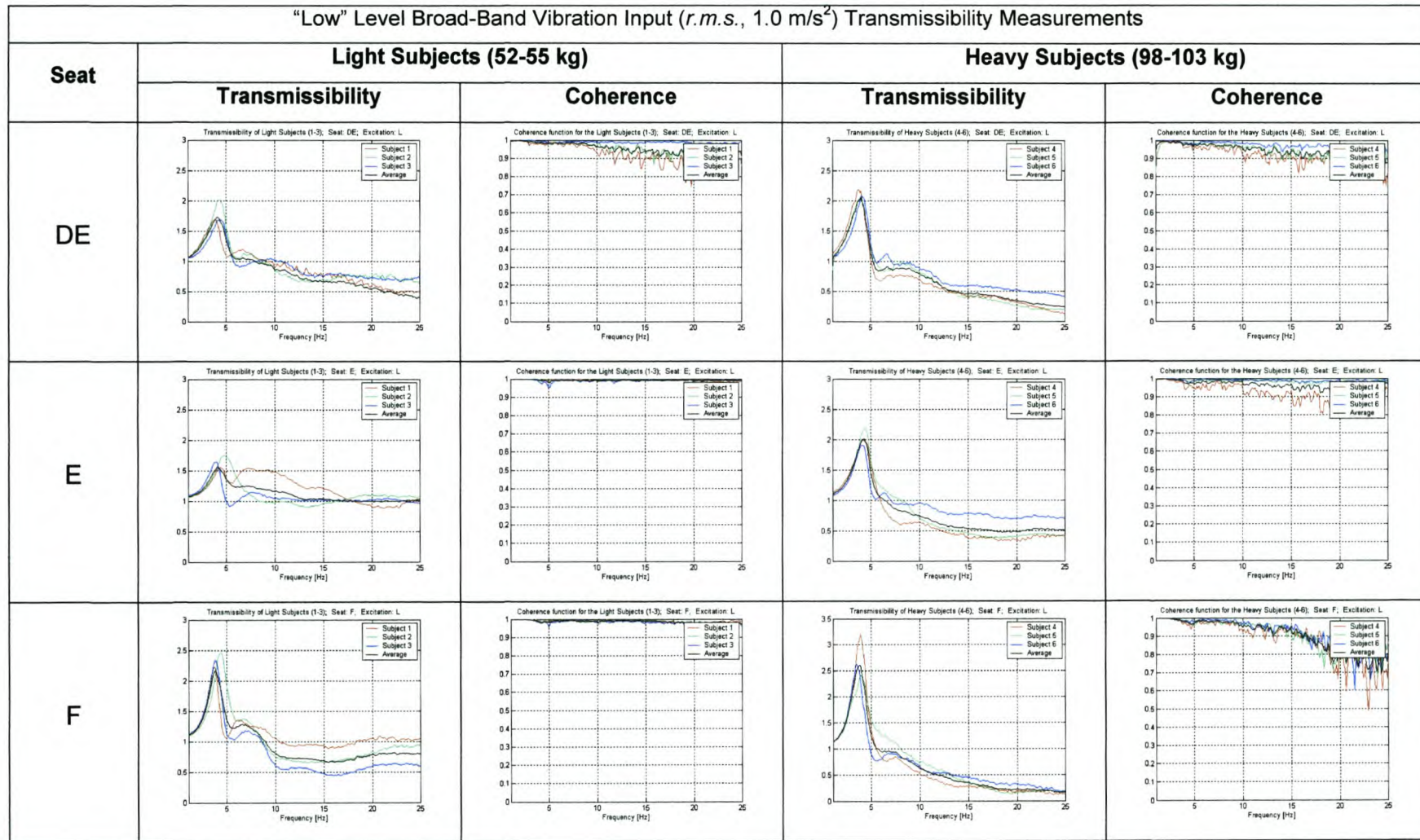
B.3. Seat Transmissibility Results (ISO 7096, 2000)

Table B.2 Seat transmissibility results obtained with the low-level broadband vibration input

“Low” Level Broad-Band Vibration Input ( <i>r.m.s.</i> , 1.0 m/s <sup>2</sup> ) Transmissibility Measurements				
Seat	Light Subjects (52-55 kg)		Heavy Subjects (98-103 kg)	
	Transmissibility	Coherence	Transmissibility	Coherence
A				
				



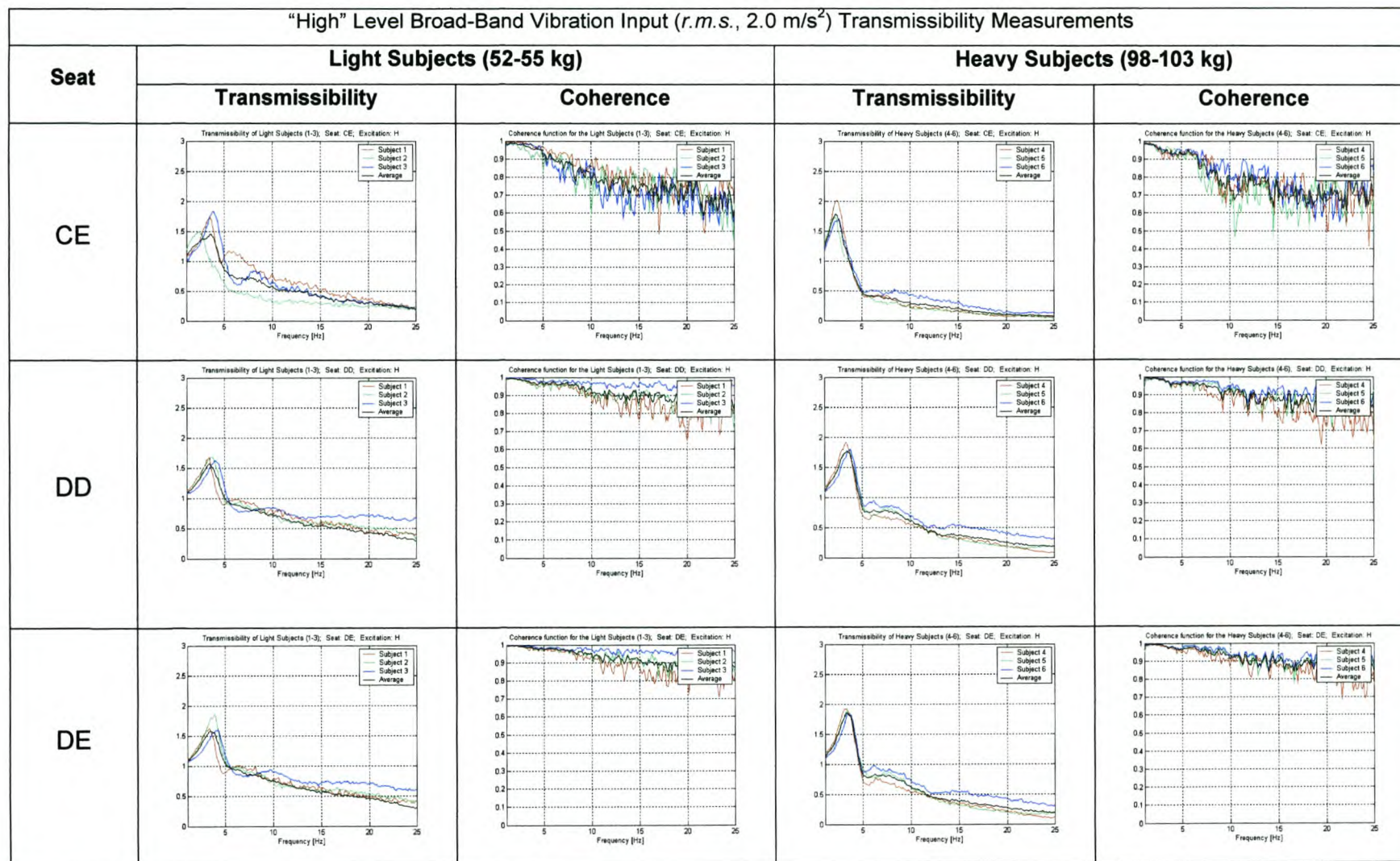


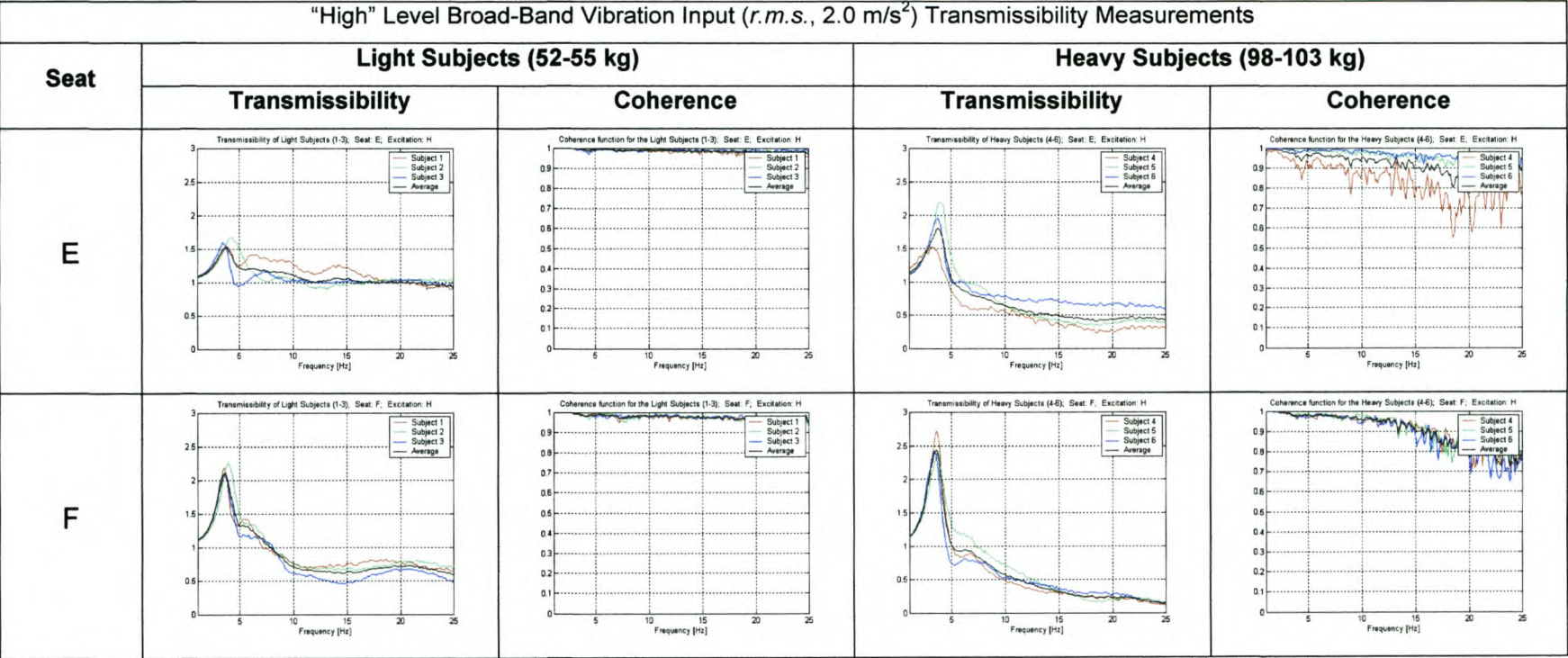


**Table B.3** Seat transmissibility results obtained with the high-level broadband vibration input  
“High” Level Broad-Band Vibration Input (*r.m.s.*, 2.0 m/s<sup>2</sup>) Transmissibility Measurements

Seat	Light Subjects (52-55 kg)		Heavy Subjects (98-103 kg)	
	Transmissibility	Coherence	Transmissibility	Coherence
A				









**Table B.4** Seat transmissibility results obtained with the modified EM5 spectral input (ISO 7096, 2000)

Approximating EM5 Spectral Input ( <i>r.m.s.</i> , 2.0 m/s <sup>2</sup> ) Transmissibility Measurements					
Seat	Heavy Subjects (98-103 kg)		Seat	Heavy Subjects (98-103 kg)	
	Transmissibility	Coherence		Transmissibility	Coherence
B			DD		
CD			DE		
CE			F		

## Appendix C: SEAT Values

### C.1. Articulated Dump Truck: ISO 7096 (2000) Spectral Analysis

**Table C.1** SEAT value estimated for the EM1 spectral input using transmissibility data obtained with the high-level broadband vibration input

Seat	Subj 1	Subj 2	Subj 3	Average*	Ave. Transm.#
A	1.22	1.21	1.23	1.22	1.21
B	1.24	1.27	1.25	1.25	1.25
CD	1.47	1.40	1.19	1.35	1.27
CE	1.36	1.36	1.33	1.35	1.30
DD	1.37	1.36	1.25	1.33	1.32
DE	1.37	1.40	1.25	1.34	1.33
E	1.23	1.23	1.28	1.25	1.25
F	1.50	1.44	1.49	1.48	1.47
Seat	Subj 4	Subj 5	Subj 6	Average*	Ave. Transm.#
A	1.32	1.41	1.24	1.32	1.31
B	1.32	1.30	1.24	1.28	1.27
CD	1.59	1.52	1.46	1.52	1.52
CE	1.71	1.48	1.50	1.57	1.55
DD	1.53	1.46	1.37	1.45	1.44
DE	1.56	1.50	1.40	1.49	1.48
E	1.38	1.44	1.40	1.40	1.38
F	1.69	1.46	1.69	1.65	1.63

\* This average is calculated as the numerical average of the three preceding, individual SEAT values in each row.

# This value is obtained using the averaged transmissibility curve for light and heavy persons respectively.



## C.2. Three-Wheeled Logger: ISO 7096 (2000) Spectral Analysis

**Table C.2** SEAT value estimated for the EM3 spectral input using transmissibility data obtained with the high-level broadband vibration input

Seat	Subj 1	Subj 2	Subj 3	Average*	Ave. Transm.#
A	1.24	1.22	1.30	1.25	1.24
B	1.21	1.28	1.26	1.25	1.24
CD	1.43	1.47	1.07	1.33	1.24
CE	1.42	1.29	1.42	1.37	1.32
DD	1.40	1.49	1.31	1.40	1.38
DE	1.41	1.42	1.31	1.38	1.36
E	1.29	1.30	1.33	1.31	1.30
F	1.62	1.59	1.61	1.60	1.60
Seat	Subj 4	Subj 5	Subj 6	Average*	Ave. Transm.#
A	1.36	1.49	1.25	1.37	1.36
B	1.30	1.29	1.16	1.25	1.23
CD	1.68	1.61	1.53	1.61	1.60
CE	1.61	1.36	1.44	1.47	1.45
DD	1.62	1.57	1.49	1.56	1.55
DE	1.59	1.52	1.45	1.52	1.50
E	1.39	1.56	1.50	1.48	1.45
F	1.88	1.76	1.81	1.82	1.80

\* This average is calculated as the numerical average of the three preceding, individual SEAT values in each row.

# This value is obtained using the averaged transmissibility curve for light and heavy persons respectively.